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AIRCRAFT DESIGNER'S HANDBOOK

FOR

TITANIUM AND TITANIUM ALLOYS

DEFENSE METALS INFORMATION CENTER
BATTELLE MEMORIAL INSTITUTE
COLUMBUS, OHIO 43201

TECHNICAL REPORT AFML-TR-67-142

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FOR

TITANIUM AND TITANIUM ALLOYS

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FOREWORD

This "Aircraft Designer's Handbook on Titanium and Titanium Alloys" represents a second edition of an earlier handbook bearing the same title, and the designation SST 65-8, dated August, 1965. This earlier version was assembled in support of the supersonic aircraft transport program that is being directed by the Office of Supersonic Transport Development under the Federal Aviation Agency and was prepared by the Columbus Laboratories of Battelle Memorial Institute under Contract No. FA-SS-65-6.

The present version retains the format of the earlier edition. However, much of the earlier information has been updated to reflect the changes in technology that have occurred since 1965. In addition, various new subsections have been incorporated to broaden the scope of subject matter covered. This revision was supported jointly by the Materials Laboratory of the U. S. Air Force and the Federal Aviation Agency.

In general, the information presented herein is representative of good engineering practice, although actual designs and fabrication processes may vary from those recommended. Also, although the design strength allowables data given in Section 5 of this handbook are presented in accordance with MIL-HDBK-5 format and procedures, these in no way supersede the approved MIL-HDBK-5 information.

Information presented in this handbook was obtained from many sources. Those cooperating included Government agencies, the titanium producers, airframe and engine companies, and many others too numerous to list individually. The practice of referencing these various sources has been followed extensively in all sections of the handbook. Superscript numbers used throughout the text are references that are listed at the end of most of the individual subsections of the handbook.

In most instances, the DMIC specialists who assisted in the revision of this handbook were the same Battelle staff members who contributed to the original handbook. These were as follows:

> Section 1 and 2 were prepared by R. A. Wood with special contributions by T. G. Byrer, R. H. Ernst, J. D. Jackson, and D. N. Williams. Section 3 was prepared by J. A. Gurklis, C. T. Olofson, and D. E. Strohecker. Section 4 was prepared by D. G. Howden, J. E. Mortland, and R. E. Monroe. Section 5 was assembled by R. J. Favor with assistance from D. P. Moon, R. C. Simon, and W. S. Hyler. F. L. Bagby served as the Project Director and General Editor of the original handbook, while D. J. Maykuth performed these tasks in the present revision.

All comments, corrections, and suggestions for additions to this handbook should be directed to:

Defense Metals Information Center
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

This technical report has been reviewed and is approved.

D. A. Shinn
Chief, Materials Information Branch
Materials Application Division
Air Force Materials Laboratory

ABSTRACT

Emphasis has been placed on the properties and fabrication characteristics of commercially pure titanium and eight titanium alloys that appear to offer promise in high-performance airframe applications. These alloys include the Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-13V-11Cr-3Al, Ti-4Al-3Mo-1V, Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si, and Ti-6Al-2Sn-4Zr-2Mo compositions.

The subjects covered and overall arrangement of the material presented is as follows:

Section 1, Metallurgy, has been prepared to serve as a reference and guideline on the basic metallurgical structure, processing, heat treatment, and stability of titanium and titanium alloys in various environments. Special attention is given to the reactive nature of titanium.

Section 2, Availability, lists the sources, nomenclature, and forms that titanium is produced in by the mills and primary fabricators of forgings, extrusions, castings, etc.

Section 3, Machining and Forming, describes currently accepted procedures and processes involved in detail parts fabrication operations.

Section 4, Joining, describes procedures for joining titanium in the buildup of components, subassemblies, and assemblies Particular attention has been given to welding.

Section 5, Mechanical and Physical Properties, contains information on either a recommended or tentative basis of the design strength allowables for commercially pure titanium and the titanium alloys covered by the handbook.

GENERAL TABLE OF CONTENTS

SECTION 1
Titanium Metallurgy

1-0 General Titanium Metallurgy

1-0.0 GENERAL GUIDELINES

Titanium is a relatively new material. Interest in titanium was stimulated in the early 1950's, when it became evident that the temperature requirements in airframe and jet-engine components were exceeding the capabilities of existing lightweight alloys. Titanium, with its low density and high melting temperature seemed to be a promising material to meet the requirements of advanced aircraft. Since the primary application of this material appeared to be in military aircraft, the United States Government supported the bulk of the research and development required to transform the metal from a laboratory curiosity into a useful structural material. The rapid growth of the titanium industry is largely due to the effectiveness of this support.

At the present time (1967), titanium and titanium alloys are used extensively in a variety of applications ranging in sophistication from critical missile and aircraft components to corrosion-resistant anodizing racks. Manufacturing concerns that have had extensive experience in fabricating this material have found that it is only slightly more difficult to handle than most of the other structural materials. As with most structural materials, certain procedures must be followed to produce high-quality end items from titanium. However, these procedures are not difficult or unusual and follow directly from a knowledge of the metallurgical behavior of the material. The philosophy followed in presenting the information in this handbook is based on the principle that an understanding of titanium metallurgy and adherence to the metallurgical laws applicable to titanium are basic to the optimum processing and use of the materials.

About 30 titanium alloys are commercially available in several mill-product forms. However, only about 10 of these compositions are used in the majority of titanium structures. About 90 percent of these applications use three unalloyed grades and the alloys Ti-5Al-2.5Sn, Ti-6Al-4V, Ti-8Al-1Mo-1V, Ti-6Al-6V-2Sn, and Ti-13V-11Cr-3Al. By far the most used of the alloys is Ti-6Al-4V. Unalloyed titanium and Ti-5Al-2.5Sn alloy also are used in quantity. For some of the newer engine applications and airframe such as that for the supersonic transport, the compositions, Ti-6Al-2Sn-4Zr-2Mo, Ti-4Al-3Mo-1V, and Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si are gaining popularity. As the titanium industry continues to mature and users grow more familiar with the available alloys, others of the titanium compositions should similarly be used more than today.

A titanium-alloy grade for a particular application can be selected on the basis of several criteria, but factors such as mill-product-form availability, strength level, ductility and toughness levels, mode of manufacture, and service environmental conditions are usually considered. Table 1-0.0-1 presents some of the salient features of the principal titanium-alloy grades and may serve, in conjunction with data found elsewhere throughout this handbook, as a start for selection of an optimum material.

1-0.1 TITANIUM ORES

Titanium is the ninth most common element in the earth's crust and is a constituent of a number of common minerals. The two most important ores of titanium are ilmenite and rutile. Rutile, essentially TiO_2, is less often found in concentrated deposits and is less commonly used to produce TiO_2 products than ilmentite ($FeO\text{-}TiO_2$), which is found in massive deposits in many parts of the world. However, rutile is the chief ore for metal winning. The known deposits of rutile and ilmenite indicate that no shortages of titanium are likely to be due to an ore shortage.

1-0.2 EXTRACTIVE METALLURGY

Titanium is an extremely reactive material, and the oxide is quite stable. Partial reduction of the oxide with carbon at high temperatures is possible, but the reaction product consists of either a brittle carbide, a carbonitride, or a heavily oxygen-, carbon-, and nitrogen-contaminated metal. In addition, the reactivity of titanium is so great that none of the known refractories can be used to contain molten titanium. As a result, reduction processes involving initial production of the tetrachloride from titanium dioxide are commonly used. The tetrachloride is relatively easily handled and purified.

Large-scale production of titanium metal from rutile involves the chlorination of the ore to form $TiCl_4$. On the other hand, production of titanium from ilmenite ores involves either smelting of the ore to produce a TiO_2 slag, acid leaching to remove iron, and chlorination to produce $TiCl_4$, or direct chlorination of the ore followed by purification of the crude $TiCl_4$ that is produced. $TiCl_4$ is liquid at room temperature. The tetrachloride is then reduced with molten magnesium (or sodium) to produce a solid, sponge-like titanium metal. The residual magnesium and magnesium chloride reaction product are removed from the titanium sponge by distillation and leaching processes.

A higher purity form of titanium is occasionally produced by thermal decomposition of TiI_4. This

TABLE 1-0.0-1. SIMPLIFIED GUIDE TO TITANIUM AND TITANIUM ALLOY PRODUCT CHARACTERISTICS AND TYPICAL APPLICATIONS

Composition (Alloy Type), percent	Guaranteed Minimum Room-Temperature Tensile Strengths: Ultimate, ksi	Yield, ksi	Processing Characteristics: Resistance to Cracking During Forging	Sheet-Forming Rating	Weldability Rating	Heat Treatable to High Strength?	Hardenability, Section Depth, inches	Typical Applications
Unalloyed	50 65 80	40 55 70	Excellent	Excellent	Excellent	No	Not hardenable	Hydraulic control valve, gyro-wheel structure, fittings, attach brackets, welded-duct halves, complex tube shapes, heat-pump channel, skin-stringer structures
Ti-5Al-2.5Sn	120	115	Fair to good	Fair	Excellent	No	Not hardenable	Transmission and gear housing, jet-engine-compressor case assembly and stator housing, droop leading edge in boundary-layer control system and duct structure
Ti-8Al-1Mo-1V	130-135	120-125	Fair	Fair	Good	No	Not hardenable	Jet-engine compressor blades, discs and housings, gyroscope gimbal housing, inner skin and frame for jet-engine nozzle assembly, experimental sheet-stringer structures, bulkhead forgings
Ti-6Al-4V	130 Age hardenable to 170	120 160	Good	Good	Fair to good	Yes	1	Jet-engine compressor blades, discs, etc., landing-gear wheels and structures, fasteners, brackets, fittings, pressure bottles, primary and secondary sheet-stringer structures, frames, fire-walls, stiffeners, gussets, and ducts
Ti-6Al-6V-2Sn	150 Age hardenable to 180	140 170	Good	--	Poor	Yes	2	Fasteners and air-intake control track, experimental structural forgings
Ti-13V-11Cr-3Al	125-130 Age hardenable to 175	120-125 165	Fair	Excellent to fair	Fair to poor[a]	Yes	7	Structural forgings, primary and secondary sheet-stringer structures, skins, frames, brackets, fittings, fasteners, tension-torsion rotor straps, and specialty uses
Ti-2.25Al-11Sn-5Zr-1Mo-0.25Si	145 Age hardenable to 180	130 160	Fair to good	--	--	Yes	2	Jet-engine compressor blades, discs, wheels, and spacers, airframe, fasteners
Ti-6Al-2Sn-4Zr-2Mo	130	120	Good	Good	Fair to good	No	Slightly hardenable	Jet-engine compressor blades, discs, wheels, and spacers, compressor case assemblies, airframe skin components
Ti-4Al-3Mo-1V	125 Age hardenable to 180	115 155	Good	Good	Fair to poor	Yes	--	Airframe components

(a) Welds are generally not heat treated because of embrittling reactions.

process is more expensive, however, and is not used extensively. Electrolytic processes using fused salt for preparing titanium metal have also been developed, but at the present time have not been used commercially.

Presently available commercial titanium is of quite high purity. The principal impurity elements are the interstitials, oxygen, carbon, and nitrogen, and the metallic element iron. These elements are normally present in the following range:

Oxygen	0.05 to 0.150 percent
Carbon	0.01 to 0.03 percent
Nitrogen	0.01 to 0.05 percent
Iron	0.03 to 0.2 percent

1-0.3 PHYSICAL METALLURGY

1-0.3.0 General Remarks

The physical metallurgy of titanium is not complex, but an understanding of the various facets of titanium behavior are essential to the proper use of this material. Unalloyed titanium exists in two crystallographic modifications, depending upon temperature. Below 1620 F, titanium exhibits a close-packed hexagonal crystal structure designated as alpha titanium. This type of crystal structure is characterized by directional properties, sensitivity to interstitial contamination, and gradual lowering of ductility at low temperatures. Above 1620 F, titanium exhibits a body-centered cubic crystal structure designated as beta titanium. This type of structure exhibits high formability, relatively low creep resistance at elevated temperatures, and ductile-brittle transition behavior. The allotropic behavior of titanium results in the development of a variety of microstructural conditions in unalloyed titanium and is the basis for the control of microstructure and properties in titanium alloys.

The extreme reactivity of titanium with the interstitial elements, especially hydrogen and oxygen, and with chloride ions, is the second important factor that must be considered in handling titanium. Most problems encountered in processing or using titanium and its alloys have been caused by some form of contamination. The elimination of possible sources of contamination is the basic requirement for the successful use of titanium.

1-0.3.1 Microstructural Characteristics[1]

The body-centered cubic or beta form of titanium cannot be retained to low temperatures in unalloyed titanium. Therefore, the microstructure of unalloyed titanium consists essentially of 100 percent close-packed hexagonal or alpha titanium. (Small amounts of iron-stabilized beta titanium are frequently observed in unalloyed titanium and in alpha-titanium alloys.) However, depending upon the method of treating the metal, alpha titanium can appear in several modifications. Three different microstructures of fully annealed unalloyed titanium are shown in Figure 1-0.3.1-1; equiaxed alpha, Widmanstatten alpha, and martensitic alpha. The latter two are frequently lumped together under the name acicular alpha. Widmanstatten alpha occurs by transformation of beta to alpha on cooling through the transformation temperature range at a moderately slow rate. A more rapid cooling rate leads to the development of martensitic alpha. Both forms of acicular alpha are therefore transformation products. Equiaxed alpha, on the other hand, can only be produced by recrystallization of material that has been significantly deformed in the alpha field. The presence of acicular alpha is therefore an indication that the material has been heated into the beta field.

Certain alloying additions to titanium result in increased stability of the beta modification. Thus, in addition to the all-alpha microstructure, titanium alloys can develop microstructures containing both alpha and beta, or even all beta. Figure 1-0.3.1-2 shows two alloys with an alpha-beta structure, one containing equiaxed alpha and one containing acicular alpha, and one alloy showing an all-beta structure. All-beta structures are usually equiaxed and are characterized by a relatively large grain size.

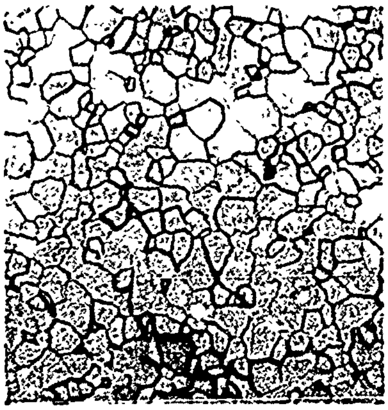
Precipitate phases are also commonly encountered in titanium alloys. These may result either from compound phases stabilized by one of the alloying additions or impurity phases, or from fine alpha rejection by an unstable beta phase. Typical examples are shown in Figure 1-0.3.1-3.

Knowledge of titanium microstructures is of considerable help in detecting hydrogen or air contamination or improper heat treatments. For example, hydrogen contamination often appears as randomly distributed needles of titanium hydride in unalloyed titanium and in alpha alloys. Air contamination can produce an alpha surface layer on alpha-beta alloys. The morphology of the alpha phase, equiaxed or acicular, present in either alpha or alpha-beta alloys indicates degree of heating into the alpha, alpha-beta, or beta fields during the processing. The shape of the alpha phase can also be used to determine the extent of the temperature rise, above the alpha-beta or beta transus, around welds.

1-0.3.2 Alloying Behavior

1-0.3.2.0 General Remarks

The microstructural changes brought about in titanium by alloying are the basis for the classification of titanium alloys into alpha, alpha-beta, or beta groups.[2] Several references on the



100X N15088

a. Equiaxed Alpha (Annealed 1 Hour at 1290 F)

100X N15087

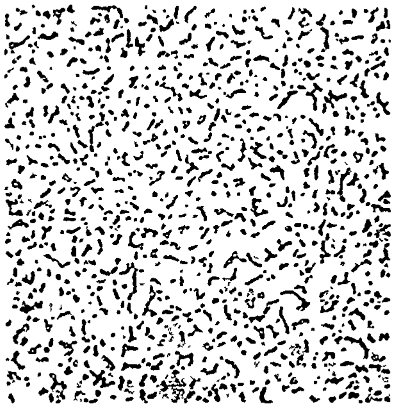
b. Widmanstatten Alpha

100X N15085

c. Martensitic Alpha

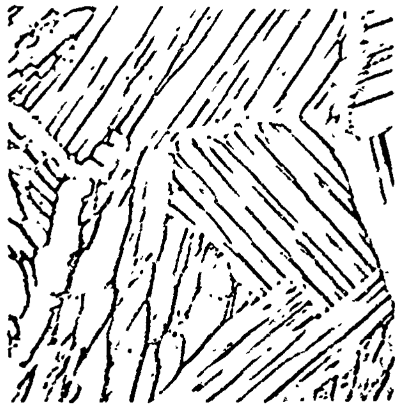
FIGURE 1-0.3.1-1. MICROSTRUCTURES OF FULLY ANNEALED TITANIUM[1]

(Reduced approximately 25 percent in printing.)



300X N32157

a. Equiaxed Alpha-Beta Structure, Ti-6Al-4V



300X N32182

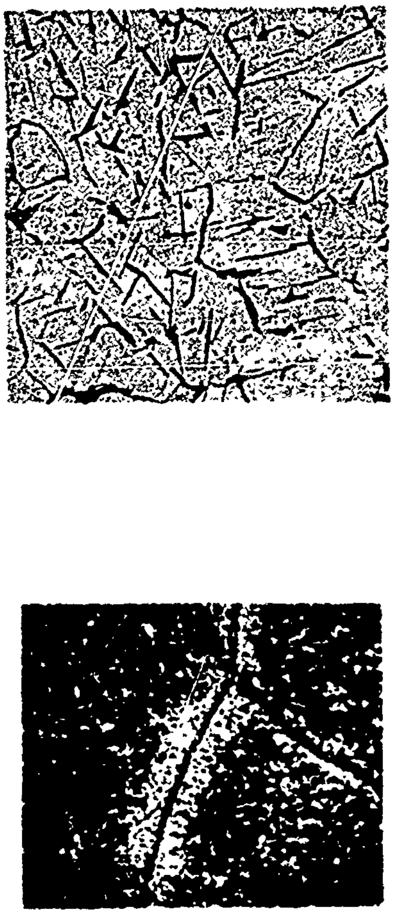
b. Acicular Alpha-Beta Structure, Ti-6Al-4V

300X N87048

c. Equiaxed Beta Strucutre, Ti-13V-11Cr-3Al

FIGURE 1-0.3.1-2. MICROSTRUCTURES OF ANNEALED TITANIUM ALLOYS[1,4] CONTAINING SOME BETA PHASE

(Reduced approximately 25 percent in printing.)



750X 6371

b. Alpha Precipitation in Ti-11Mo Alloy

FIGURE 1-0.3.1-3. MICROSTRUCTURES OF ANNEALED TITANIUM ALLOYS CONTAINING COMPOUND OR PRECIPITATE PHASES[1]

(Reduced approximately 25 percent in printing.)

alloying behavior, phase relationships, and microstructural conditions that occur as a result of alloying are available.[1-6] Those additions that increase the beta-transus temperature or that show extensive or complete solubility in alpha titanium are referred to as alpha stabilizers, while those that decrease the beta transus are referred to as beta stabilizers. Beta-stabilizing additions are of two types, beta isomorphous, in which sufficient alloying stabilizes beta to room temperature, and beta-eutectoid, in which the beta becomes unstable at some temperature above room temperature. In many cases, alloys of the latter type can be heat treated to retain untransformed beta to room temperature.

1-0.3.2.1 Alpha Stabilizers

The principal alloying additions used in alpha-titanium alloys are aluminum, oxygen, tin, and zirconium. These additions can be alloyed in titanium to develop high-strength alloys having all-alpha structures. Alpha alloys are characterized by good strength, creep resistance, weldability, and toughness. Oxygen, however, which forms an interstitial solid solution in alpha titanium, is damaging to toughness. The most useful addition is aluminum, which can be added in amounts up to 8 percent. Larger amounts of aluminum result in the development of unstable alloys that become embrittled on exposure to temperatures of 800 to 1100 F. Embrittlement is the result of a phase change in the Ti-Al alloy system. The exact nature of this phase change is not understood as yet, but it apparently involves the formation of an ordered structure quite similar in lattice dimension to alpha.[3]

1-0.3.2.2 Beta Stabilizers

A number of alloying additions act as beta stabilizers in titanium. These include such additions as manganese, iron, chromium, vanadium, molybdenum, and columbium.

Alpha-beta alloys normally contain sufficient alloying additions to stabilize from 10 to 50 percent beta phase to room temperature. They may also contain concurrent additions of alpha-soluble elements such as aluminum to strengthen the alpha phase. Alpha-beta alloys show good fabrication characteristics, high room-temperature strength, and moderate elevated-temperature strength. Unless the amount of beta present in the alloy is small--about 20 percent or less--they are not weldable. Since the beta phase of alpha-beta alloys is usually unstable, these alloys are often heat treated to obtain precipitation reactions in the beta, resulting in high strength levels. Exposure at moderate temperatures (800 F) can lead to embrittlement due to omega formation in the beta phase. Omega is an extremely embrittling transition phase that forms on low-temperature precipitation of alpha from an unstable beta.

All-beta titanium alloys generally contain large amounts of one or more of the beta isomorphous additions--molybdenum, columbium, vanadium, and tantalum. Small amounts of alpha stabilizers may also be used concurrently with beta-stabilizing elements as in alpha-beta alloys. These alloys can also be made responsive to age hardening by proper balancing of alloying additions. Beta alloys are extremely formable, and are also weldable. However, subsequent heat treatment of welded beta alloy is not reliable, since base metal and weld metal strengthen at different rates, which can result in the embrittlement of the weld metal.

1-0.3.3 Interstitial Contamination

1-0.3.3.1 Oxygen and Nitrogen

Both oxygen and nitrogen are alpha stabilizers and show extensive solubility in alpha titanium. Unfortunately, they tend to embrittle titanium when they are present in fairly small amounts. Nitrogen is generally less troublesome than oxygen because it is absorbed at a lower rate. Oxygen contamination is a major problem in all operations where titanium or its alloys are heated above about 1200 F in air. The rate of scale formation on titanium when heated in air at 1400 F and above is quite rapid.(5) However, scale is readily seen and can be removed without undue difficulty. The diffusion of oxygen into the metal to form a hard, brittle surface layer is more difficult to detect and can have a serious effect on properties.

Easily removed coatings to reduce contamination rates in air have been developed. Their use can significantly retard the rate of contamination during heat treatment in air. The use of inert or vacuum preheating or heat treating equipment is also beneficial. For many operations, however, it is more economical to handle the part in air and to remove the contaminated layer after processing by acid pickling or other suitable techniques.

It is desirable to remove any contaminated surface layer prior to any reheating process because exposure to temperature results in its penetration to a greater depth.

1-0.3.3.2 Hydrogen(6)

Hydrogen forms a beta-eutectoid system with titanium. The diffusion rate of hydrogen in titanium is quite rapid, and under proper conditions, such as acid pickling or exposure to very high-pressure hydrogen, hydrogen contamination can occur at room temperature. Quite small amounts of hydrogen, as low as 150 to 200 ppm can drastically reduce ductility under certain circumstances. Alpha and alpha-beta alloys can fail in a brittle manner at stresses well below their yield strength when hydrogen is present. Residual stresses from forming or assembly mismatch have been found adequate to initiate failure in such contaminated material.

At the present time, hydrogen is maintained at a low level in commercial products by vacuum-melting and annealing treatments. A hydrogen specification on incoming material is used to ensure that hydrogen is not present in excessive amounts in material supplied to the user. Current problems with hydrogen contamination appear to arise primarily from three sources: improper acid-pickling treatments, chem-milling, and attemps to use titanium in contact with hydrogen at too high a temperature. Care should be used to ensure that pickling and chem-milling solutions are properly balanced to minimize pickup. If pickup does occur, vacuum annealing should be considered as a method of salvaging the part.

Hydrogen can be removed from titanium by vacuum annealing without adverse effects resulting from its presence if the level of contamination was not sufficiently high to have caused cracking during fabrication.

1-0.4 PROCESS METALLURGY

1-0.4.0 General Remarks

The processing of titanium sponge to a useful fabricated shape must be carried out so as to avoid contamination of the metal or alloy. Titanium reacts readily at elevated temperatures with the constituents of air, and forms heavy oxide and nitride scales at temperatures above about 1200 F. Unfortunately, both oxygen and nitrogen dissolve readily in titanium metal, and their presence is damaging to the properties of the fabricated product. Oxygen is more reactive than nitrogen, and also diffuses into the metal or alloy more rapidly. Therefore, oxygen contamination is the most serious problem in processing titanium. Once it is present in solution in the metal or alloy, oxygen cannot be eliminated except by removing the contaminated metal layer. Hydrogen also readily dissolves in titanium, and is damaging to properties. It can be removed by vacuum treatment, however. Although hydrogen is produced by reaction of titanium with water vapor at elevated temperature, the oxide scale that forms on titanium as a product of the reaction retards hydrogen absorption.

1-0.4.1 Melting and Casting

The production of titanium ingots from sponge titanium is accomplished by consumable-electrode arc melting into a water- or liquid-metal-cooled metallic crucible. Melting is accomplished in vacuum or under a low partial pressure of inert gas such as argon or helium. The reactivity of titanium with all potential crucible materials makes most other conventional melting processes useless in melting titanium and its alloys.

Double melting is usually employed to insure homogeneity. The use of vacuum melting for the production of ingots has the advantage of largely eliminating hydrogen and magnesium impurities present in the sponge. As a result, consumable-electrode vacuum-melted ingots are normally of higher purity with respect to hydrogen and $MgCl_2$ than the sponge metal used in preparing the electrodes. Alloying is accomplished by incorporating the desired alloying additions into the pressed electrode shape either as pure-metal additions or as master alloys.

Titanium ingots as large as 9500 pounds are currently made by the consumable-electrode process.

Titanium is not used extensively in the cast form, but castings up through 200 pounds can be made by patented processes that involve melting so as to form a titanium liner or skull in the crucible and casting into rammed graphite or shell molds. The latter yields a precision-cast product that is finding use in current aircraft gas-turbine engines.

1-0.4.2 Ingot Forging

Titanium ingots are machined to remove surface defects present on the ingot prior to fabrication. Most breakdown fabrication is done by press forging at temperatures of 1800 to 2200 F. Heating can be accomplished in an air furnace maintained with a slightly oxidizing atmosphere to minimize hydrogen absorption. During forging, coatings are applied to avoid excessive oxidation, but a heavy scale is still formed on the billet surface. This scale, and the oxygen-contaminated metal beneath the scale, are removed after forging by sand blasting and surface grinding. The heating time during forging is kept as short as possible to minimize the depth of the contaminated layer.

A considerable portion of titanium mill products are furnished as forged bar or billet for subsequent machining, die forging, or other fabrication.

1-0.4.3 Rolling

Titanium and titanium alloys are reduced to plate or sheet by hot rolling in most cases. Forged billets are normally used as the starting material. Rolling is done between about 1500 and 1800 F. Heating is done in air furnaces or argon furnaces. Pack rolling in steel cans is often used to obtain the thinner sheets. Surfaces are cleaned of parting compound, oxide, and contamination after rolling by combinations of grinding, grit blasting, and acid pickling, depending on thickness.

Because of contamination problems, thin sheet is usually cold rolled to final thickness. The high strength of titanium from room temperature to 800 F makes gage control during cold rolling extremely difficult. Senzimir mills are usually required for the rolling of sheet to less than 20 mils thickness. Annealing of thin sheet must be in vacuum or inert atmosphere to prevent contamination, even though the annealing temperature is usually less than 1600 F.

1-0.4.4 Extrusion[7]

The basic extrusion process employed for the production of long titanium sections is forward extrusion in horizontal hydraulic presses. The billet is contained in a ci cular chamber and forced through an open die located at one end of the chamber. The movement of metal in passing through the die cavity is in the direction of ram movement.

The major differences in processing center around such variables as extrusion lubricants, billet heating, die materials and design, and extrusion speed. To facilitate rapid extrusion with the least possible force, the general practice has been to extrude at the highest temperature consistent with good mechanical properties. For commercially pure titanium, temperatures as high as 1900 F--well into the beta-phase region--have no serious effect on mechanical properties. In practice, however, it has proved practical to extrude at temperatures in the vicinity of 1700 F.

For titanium alloys, temperature is more critical because of the possible effects of beta transformation on the mechanical properties. Alpha-beta alloys generally suffer a loss of ductility when heated in the beta-phase region. In some instances, annealing or heat treating will restore sufficient ductility to the alloy for certain applications requiring lower strength. Similarly, optimum mechanical properties are attained in alpha alloys such as the commercial Ti-5Al-2.5Sn alloy by extruding at temperatures below the beta transus.

1-0.4.4.1 Lubrication

Two basic types of lubricants are used for extruding titanium: (1) greases containing solid-film lubricants such as graphite and (2) glass. Metallic copper coatings are also used by some extruders. Because of the severe galling characteristics of titanium, lubrication is particularly important, is probably the most difficult problem, and represents the major differences in practice employed by titanium extruders.

Ineffective lubrication not only causes titanium pickup on the die, but also excessive die wear, with an accompanying loss of dimensional tolerance. Either of these conditions can produce deep scoring and tearing of the surface.

1-0.4.4.2 Heating

It is necessary to maintain titanium billets as nearly scale-free as possible during heating. Various means have been employed for heating billets--salt bath, induction, and argon-atmosphere furnaces. Best results have been obtained in the muffle furnace under an argon atmosphere. The use of low-frequency induction heating in an inert atmosphere has also been successful.

1-0.4.4.3 Die Life

Die Life is a function of the geometry of the shape and the grade of titanium extruded. For a given shape, die life will be substantially longer in extruding a relatively soft metal such as unalloyed titanium than for a higher strength alloy grade such as Ti-6Al-4V. Using glass lubricant, die life has varied from 1 to 20 extrusions per die.

1-0.4.4.4 Extrusion Speed

High extrusion speeds are preferre 'hether grease or glass is used as the lubricant. As grease lubricants offer little protection from the high extrusion temperatures, the hot billet should be in contact with the die for as short a time as possible. With glass acting as an insulator between billet and tools, these problems are not severe. However, the basic principle of glass lubrication--glass in a state of incipient fusion. flowing continuously from a reservoir--requires high extrusion speeds.

The actual ram speed attaina' ing extrusion varies with alloy composi' , extrusion temperature, and extrusion ratio, but is generally in the range of 200 to 300 inch per minute.

1-0.4.4.5 Finishing

The methods of processing after extrusion have differed considerably among various companies. Straightening and detwisting are almost universal requirements for structural shapes, whether they be for airframes, engines, or any other application. Hydraulic torsional stretchers are usually employed, although some companies use roll or punch straightening machines.

Commercially pure titanium can be straightened either cold or hot with little difficulty, according to most extruders. Commercial alloys, however, are extremely difficult to cold straighten because of their high yield strengths and particularly, because of springback. It has usually been necessary to straighten at temperatures of about 700 to 1000 F. Warm-redrawing techniques in this temperature range also are being developed.

Before further processing, the glass adhering to the surface of shapes extruded by the glass process must be removed by quenching the hot extrusions, pickling, or shot blasting. Therefore, reheating is generally necessary before straightening and detwisting.

Contaminated surface scale is usually removed after extrusion by vapor blasting and pickling.

1-0.4.5 Die Forging

Compositions and selected forging characteristics of several titanium alloys used for forgings are presented in Table 1 0.4.5-1[8].

Initial breakdown forging of titanium alloy ingots is usually done at temperatures above the beta transus because the body-centered cubic structure is more ductile and forging-pressure requirements are generally lower. Final forging is usually done at temperatures below the beta transus to achieve the structure having optimum properties and to prevent excessive beta-grain growth and attendent low ductility.

Variations in strain rate have little influence on the forgeability of alpha and alpha-beta alloys; both alloy types are readily forgeable in either presses or hammers. The Ti-13V-11Cr-3Al beta alloy also exhibits good forgeability on both presses and hammers when forged above 1400 F. However, since titanium alloys exhibit rapidly increasing strengths with increasing strain rate, more energy is required for hammer forging than for press forging at comparable temperatures. The Ti-13V-11Cr-3Al alloy forged t 1450 F for example, requires nearly 50 perc t more energy at a typical hammer velocity of 200 inches per second than at a typical press velocity of 1.5 inches per second. For equal reductions during 1800 F hammer forging, the energy required to deform Ti-13V-11Cr-3Al is about twice that for AISI 4340 steel.

Forging pressures for each of the three types of titanium alloys increase more rapidly with decreasing temperature than does that of low-alloy steels. Thus, in ordinary die-forging operations, cooling the workpiece has a more critical effect on raising forging pressures of titanium than of steels.

There are a number of factors that make titanium alloys more difficult to forge than steels. The metallurgical behavior of the alloys not only imposes certain controls and limitations on the forging operation but influences all of the steps in manufacturing forged parts. Particular care is necessary throughout the processing cycle to avoid contamination by oxygen and/or hydrogen, which can severely impair the properties and over-all quality of a forged part.

Heating is generally done in an oxidizing atmosphere to minimize hydrogen pickup. Inert-gas atmospheres may be used for parts having extremely thin sections. Contaminated surface layers are generally removed by a 3%HF-30%HNO_3 pickle. Hydrogen can be removed only by vacuum annealing.

The hard surface scale formed on titanium is very abrasive, and care must be taken to provide

TABLE 1-0.4.5-1. FORGING CHARACTERISTICS OF TITANIUM ALLOYS COMMONLY USED FOR DIE FORGINGS[8]

Composition (Balance Ti), %	Alloy Type	Approximate Beta-Transus Temperature, F	Forging, Temp, F Breakdown Forging	Die Forging	Relative Pressure Requirements for Press Forging
Unalloyed Ti	Alpha	1650	1700-2000	1550-1700	0.6
Ti-5Al-2.5Sn	Alpha	1900	1700-2000	1775-1850	1.0
Ti-8Al-1Mo-1V	Alpha	1900	1700-2000	1775-1850	1.1
Ti-6Al-4V	Alpha-beta	1810	1800-2000	1650-1800	1.0
Ti-6Al-6V-2Sn-1(Fe, Cu)	Alpha-beta	1735	1725	1575-1625	1.1
Ti-13V-11Cr-3Al	Metastable beta	1325	1600-1900	1600-1800	1.4
Ti-2.25Al-11Sn-5Zr 1Mo-0.2Si	Alpha-beta	1730	1825	Below 1675	1.1
Ti-6Al-2Sn-4Zr-2Mo	Alpha-beta	1820	--	Below 1775	1.1

adequate lubrication during forging to minimize die wear as well as to provide lubrication.

Because of the low elastic modulus and relatively high strength of titanium alloys, forgings are difficult to cold straighten either by coining or reverse bending. Such operations are usually done at temperatures between 700 and 1000 F. At times, it is helpful to maintain a straightening load on a forging for a few seconds to take advantage of "creep". This technique is especially useful for removing large warpages. Creep-resistant alloys (e.g., Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V) require straightening temperatures upwards of 1000 F, especially if straightening requirements are severe. Forgings having severely contaminated surfaces are apt to crack during straightening. Hence, contamination should be removed beforehand.

Detailed considerations of the forgeability and metallurgical behavior of titanium are available in DMIC Report 141[9] and ASD TR 61-7-876.[10]

1-0.4.6 Forming

The combination of high yield strength and low modulus of titanium and its alloys leads to large amounts of springback during forming operations. Hot sizing is generally required to produce close-tolerance parts. The uniform elongation of titanium reaches a maximum in the vicinity of 500 F. Difficult forming operations are generally more successful if carried out with moderate heating. Care must be taken during forming operations to avoid contamination of the sheet surface with excessive oxidation or sources of chloride ions (masking tape, chloride cleaners, some marking pencils), or with fingerprints, since these can result in stress-corrosion failures during stress-relief annealing or hot sizing. Oxidation products are usually cleaned off finish-formed parts by one of several processes. Detailed information on titanium forming operations is given in Section 3.

1-0.4.7 Machining

Titanium is similar to austenitic stainless steels in its machining behavior. Excellent machined surfaces are usually obtained.

Because of the lack of metal buildup ahead of the tool and the high shear angle characteristic of titanium, tool wear rates tend to be high, and high tool temperatures are commonly encountered. These factors, combined with titanium's extreme reactivity with air at higher temperatures and its marked galling tendencies, tend to make cutting reasonably difficult. Machining is facilitated by procedures designed to minimize tool-tip temperatures such as low cutting speeds, heavy feeds, and heavy use of coolants. Machines for machining titanium must be rigid, and tools must be kept sharp. Recommended machining procedures for titanium and titanium alloys are described in Section 3 of this handbook.

Chem-milling is frequently used to remove metal in the preparation of titanium parts. It is important to control this process carefully to avoid excessive hydrogen contamination. If excessive hydrogen is absorbed during chem-milling, vacuum annealing can be used to reduce the hydrogen content to an acceptable level.

1-0.4.8 Joining[11]

Unalloyed titanium and alpha-titanium alloys are readily joined by welding. All welding processes commonly used to join metals are applicable to titanium, including arc, spot, seam, flash, and

pressure welding. However, protection of the molten metal pool from atmospheric contamination is essential during the arc welding of titanium. Inert-gas shielding is used extensively. Pickup of oxgyen, nitrogen, or hydrogen during welding leads to weld embrittlement. Care must also be taken to avoid salt corrosion failures during stress-relief treatments of weldments by avoiding finger prints, chloride compounds from cleaning agents, and from marking crayons, etc. The ductility of properly protected welds is equal to that of the base metal. Alpha-beta alloys containing more than about - percent (by volume) beta are difficult to weld without weld embrittlement. Beta alloys may be welded satisfactorily, but weld embrittlement is a problem during subsequent aging of precipitation-hardening alloys. Welding of titanium to other materials generally results in embrittlement due to the formation of intermetallics.

Titanium alloys are readily joined by pressure welding using either gas-pressure bonding or roll-welding methods. Pressure welding of titanium is facilitated by the high solubility of surface oxides in the metal at elevated temperatures.

The joining of titanium is described in detail in another section of this handbook.

1-0.4.9 Heat Treatment[12]

Titanium and its alloys are normally heat treated after fabrication to control the amount of residual stress or to produce age hardening. Stress-relief annealing is conducted at temperatures ranging from 1050 F for unalloyed titanium to 1400 F for highly alloyed alpha alloys. Recrystallization annealing treatments range from 1200 to 1600 F. Although precipitation-hardening treatments are normally conducted at low temperatures, 600 to 1100 F, the desired solution heat treatment temperature may be high as 1750 F.

Contamination during heat treatment increases rapidly with increased temperature, and treatments above 1200 F in air result in heavy scale formation. High temperature treatments must be carried out in vacuum or with inert gas protection unless subsequent removal of the scale formed at high temperatures is possible. At lower temperatures, heat treatment in air is feasible if followed by removal of the thin, contaminated surface layer. Heat treatment in air furnaces should be conducted with slightly oxidizing atmospheres to avoid hydrogen pickup.

Since diffusion of oxygen into the metal is rapid at elevated temperatures, any scale or surface contamination present on the fabricated part should be removed before heat treatment.

Vacuum-annealing treatments are used to remove hydrogen when contamination from this element is present. Hydrogen removal preferably should be carried out above 1200 F.

1-0.5 CORROSION BEHAVIOR

1-0.5.0 General

Titanium is inherently a reactive metal, so that whenever it is exposed to air or other environments containing available oxygen a thin surface film of oxide is formed. It is to this film that titanium owes its excellent corrosion resistance.

The most protective films on titanium are usually developed when water, even in trace amounts, is present in the environment. For example, if titanium and its alloys are exposed to some strongly oxidizing environments in the absence of mositure, the film that is formed is not protective, and rapid oxidation, often pyrophoric in nature, may take place.

Examples of such reactions that may be initiated at room temperature or slightly above are (1) titanium and dry chlorine[13, 14] and (2) titanium and dry fuming nitric acid.[13]

1-0.5.1 Chemical Environments

Titanium and its alloys corrode rapidly in environments that cause breakdown of the protective films. Of most importance are such reagents as hydrofluoric, hydrochloric, sulfuric, phosphoric, oxalic, and formic acids. However, attack by all these media except hydrofluoric acid can be reduced in many instances by the addition of acid salts, oxidizing acids, and other suitable inhibitors. Dry chlorine also attacks titanium, but it is quite resistant in wet chlorine (1% moisture) and other oxidizing gases, such as SO_2 and CO_2.

Titanium has excellent corrosion resistance to all concentrations of nitric acid up to 350 F. Even at 550 F the rate of attack in 20% HNO_3 is only 12 mils/yr. An anomaly exists, however, at 375 F, in that corrosion rates as high as 100 mils/yr are reported at concentrations above 20 percent HNO_3[15]. Caution should be exercised, however, when titanium alloys are used in anhydrous fuming HNO_3 because the reaction can be pyrophoric. The resistance of titanium to chromic acid is good, as is its resistance to aqua regia ($3HCl \cdot 1HNO_3$). For mixtures of sulfuric and nitric acids, corrosion rates increase with increasing H_2SO_4 concentration.

Titanium, like a number of other metals, has good resistance to dilute solutions of alkali. Hot, strong, caustic solutions will attack unalloyed titanium and titanium alloys. On the other hand, there is no evidence to suggest that titanium alloys are susceptible to caustic embrittlement as are carbon steels and stainless steels.

Titanium is superior to stainless steels in its resistance to corrosion and pitting in marine environments and most neutral chloride solutions. The main exceptions are boiling solutions of aluminum chloride, stannic chloride, cupric chloride, zinc chloride, magnesium chloride, and calcium chloride, which will cause pitting of titanium alloys. In addition, at temperatures above about 200 F, titanium may evince crevice corrosion in sea water and bromine. On the other hand, titanium is not attacked by the highly corrosive ferric chloride and sodium hypochlorite solutions, under conditions too severe for stainless steels.

Pure hydrocarbons are not considered corrosive to most metals, including titanium. In addition, titanium exhibits good corrosion behavior in most chlorinated and fluorinated hydrocarbons, and other similar compounds used as hydraulic and/or heat-exchange fluids. It should be pointed out, however, that such materials may hydrolyze in the presence of water, forming HF or HCl, which in turn may attack titanium. In addition, at elevated temperatures, these hydrocarbons may decompose, liberating hydrogen, a portion of which may be absorbed by the titanium, resulting in loss of ductility, or chlorides may be released that can initiate elevated-temperature stress-corrosion cracking.

Tiatnium is not recommended for use in gaseous or liquid oxygen since a violent reaction can occur.[16] When a fresh titanium surface such as a crack or fracture is exposed to gaseous oxygen, even at -250 F and at a pressure of about 50 to 100 psi, burning can begin. Once the reaction starts, the oxide formed is not protective, as it is, for example, with stainless steel. In liquid oxygen, titanium is impact sensitive at levels below those of mahy organics. Titanium and its alloys also exhibit pyrophoric reactions under impact in chlorine trifluoride, liquid fluorine, and nitrogen tetroxide. However, only in the case of liquid and gaseous oxygen has the reaction been found to propagate once it was initiated.

1-0.5.2 Special Forms of Corrosion

1-0.5.2.1 Stress-Corrosion Cracking, Ambient Temperature

Stress-corrosion cracking can be defined as a form of localized failure that is more severe [illegible] the combined action of static tensile stresses and corrosion that would be expected from the sum of the individual effects of stress and corrosion acting along. It is characterized by a brittle-type fracture occurring in an otherwise ductile material. The surface direction of the cracks is perpendicular to the direction of the stress load. Cracking may be either intergranular or transgranular, depending on the alloy, the structure, and the environment. In general, stress-corrosion cracking of titanium alloys is intergranular.

Commercially pure titanium has not been found to fail by stress-corrosion cracking in any media except fuming HNO_3 or methanol containing HCl, H_2SO_4, or Br.[17] However, under "plane strain" conditions, unalloyed titanium containing high oxygen levels will exhibit rapid crack propagation in seawater at low stress levels. This phenomenon is though by many to be akin to stress corrosion cracking. The common agueous stress-corrosion test solutions do not have any effect on titanium alloys under normal conditions. However recent tests have disclosed that titanium alloys under exposure conditions of ambient temperature, aqueous media, and in a state of stress that produces a virgin metal surface (a fresh crack), will show property deterioration.[17] In particular, it has been found that some common aqueous stress-corrosion solutions (distilled water, tap water, 3.5% NaCl solution) affect the fatigue life of sharp-notch test specimens (at high stress levels) and cause reduced stress rupture life in fatigue-cracked tension and bend specimens. In the latter case, cracking propagates very rapidly from the infinitely sharp fatigue-induced notch in a direction normal to the direction of the tension stress. A fresh titanium surface is continually being exposed to the test medium in this type of test. Under these conditions, it appears that the titanium materials, as well as some other structural materials tested, undergo a stress-corrosion type of deterioration. The same effect was observed in steels[18, 19] and was commonly used to speed up crack development in the preparation of fatigue-precracked fracture-toughness specimens.[20] While the practical limitations imposed by this ambient-temperature reaction are presently unknown, it is entirely clear that titanium alloys are not immune from such reactions, as was previously believed.

The susceptibility of precracked titanium alloys to stress-corrosion cracking in salt water appears to be affected by the aluminum and tin content and isomorphous beta stabilizers. The data indicate that the susceptibility occurs with higher aluminum or aluminum-tin contents. A notable exception to this general trend is the susceptibility of the Ti-8Mn alloy. The presence of isomorphous beta-stabilizers--molybdenum, vanadium, and columbium--tends to reduce the sensitivity of titanium alloys. Titanium alloys containing 5 to 7 percent aluminum plus 1 to 4 percent vanadium and/or molybdenum were found to be insensitive. The addition of molybdenum to Ti-7Al-2Cb-1Ta or Ti-7Al-3Cb tended to reduce their susceptibility to cracking, and the addition of molybdenum is currently being considered as a compositional improvement for certain alloys in order to reduce their cracking potential in salt water.

Alloys that have shown some degree of susceptibility to rapid crack propagation in salt water are listed below, but not necessarily in order of susceptibility:[17]

Unalloyed Ti[a]	
Ti-8Mn	Ti-6Al-4V-1Sn
Ti-2.5Al-1Mo-11Sn-5Zr-0.2Si	Ti-6Al-4V-2Co

Ti-3Al-11Cr-13V	Ti-6Al-6V-2.5Sn
Ti-4Al-4Mn	Ti-7Al-2Cb-1Ta
Ti-5Al-2.5Sn	Ti-7Al-3Cb[b]
Ti-6Al-2.5Sn	Ti-7Al-3Mo
Ti-6Al-4V	Ti-7Al-3Cb-2Sn
Ti-6Al-3Cb-2Sn	Ti-8Al-1Mo-1V
	Ti-8Al-3Cb-2Sn

(a) With high oxygen content, i.e., 0.317 percent.
(b) As received and beta annealed.

Preliminary screening tests indicate the following alloys to be insensitive to salt-water crack propagation for the condition used:

Ti-2Al-4Mo-4Zr	Ti-6Al-2Sn-1Mo-3V
Ti-4Al-3Mo-1V	Ti-6Al-2Cb-1Ta-0.8Mo
Ti-5Al-2Sn-2Mo-2V	Ti-6.5Al-5Zr-1V
Ti-6Al-2Mo	Ti-7Al-2.5Mo[a]
Ti-6Al-2Sn-1Mo-1V	

(a) As received and beta annealed + WQ + 110 F, aged for 2 hr.

The degree of susceptibility of some titanium alloys to stress-corrosion cracking in salt water can be changed by the heat treatment given the material. In general, rapid quenching from temperatures above the beta transus tends to improve resistance, while aging in the 900 to 1300 F range tends to decrease resistance to accelerated cracking.

Alloys of titanium can also suffer stress-corrosion cracking at ambient temperatures under certain other specific conditions. Failures have been encountered in red fuming HNO_3 (as mentioned above), in N_2O_4, and in HCl. In addition, certain alloys have shown susceptibility to stress-corrosion cracking in chlorinated-hydrocarbon solvents. Cracks will initiate and propagate only if the right combination of stress, metallurgical history, and environmental factors is present.

In the case of red fuming HNO_3, cracking is limited to environments containing less than 1.5% water or more than 6% NO_2. The cracking is thought to be related to the selective attack of small amounts of beta-phase and/or an enriched-alloy zone along the grain boundaries. In addition, this attack leaves finely divided, highly reactive particles of titanium which will detonate under slight shock. Adding water above 1.5% to the anhydrous acid greatly reduces the chance for stress-corrosion cracking and pyrophoric reactions.

Failure of the Ti-6Al-4V alloy in tankage applications has occurred in N_2O_4 containing oxygen and chlorides as impurities. With the oxygen replaced by greater than 0.06 percent NO as an inhibitor, failures are prevented. This attack may be the result to incomplete oxide formation at the metal-surface slip planes, or by preferential absorption of the chloride ion. Current specifications for propellant-grade N_2O_4 require the NO content to be between 0.4 and 0.8 percent.

Methyl alcohol is another medium that initiates stress-corrosion cracking of titanium and its alloys. With small additions of bromine, HCl, or H_2SO_4 to methanol, even unalloyed titanium can be made to crack.[17] With chemically pure methanol, the susceptibility of titanium alloys varies, depending on alloy, heat treatment, and stress level. For example, solution-treated-and-aged Ti-6Al-4V evinces some failures at about 70 percent of its yield strength, while annealed Ti-6Al-4V cracks only on stressing near its yield point. The Ti-8Al-1Mo-1V alloy appears even more susceptible.

1-0.5.2.2 Stress-Corrosion Cracking, Elevated Temperatures

Late in 1955, surface cracking was observed on Ti-6Al-4V alloys undergoing creep testing at 700 F. The cracking was attributed at that time to surface embrittlement induced by oxidation. Later, it was established that cracks were often associated with fingerprints. Testing of specimens under stress in contact with pure NaCl produced cracking at elevated temperatures. This phenomenon has become known as hot-salt stress-corrosion cracking.

While cracking of titanium alloys in contact with hot sodium chloride has been obtained in laboratory studies at temperatures as low as 450 F, this phenomenon has not been officially reported as the cause of failure of a titanium part in service.[17,21] It should be pointed out, however, that, with the possible exception of jet-engine components, titanium parts in service are not subjected to combinations of stress and temperature in the range found to induce cracking in the laboratory.

Studies to date have indicated that several types of chloride salts will initiate failure. However, NaCl now appears to be most reactive. Oxygen or a reducible oxide (TiO_2) must also apparently be present for cracking to occur, although the critical concentration of oxygen is low (1 to 10 microns Hg pressure). Water may also enter into the reaction and appears to be necessary, although its critical concentration is low (on the order of 10 ppm).

Recent studies on the mechanism have shown that a gas-phase reaction can occur, whereas previously a liquid-phase reaction seemed to be required. The mechanism apparently involves NaCl, O_2, H_2O, and reaction products of $TiCl_2$, NaOH, and TiO_2. A possible reaction is:

$$2NaCl + Ti + 1/2O_2 + H_2O \rightarrow TiCl_2 + 2NaOH$$
$$(\Delta F = -40 \text{ kcal at } 600 \text{ K}).$$

An unstable intermediate such as $TiCl_2$ is indicated by the cyclic studies (room temperature to operating temperature) in which reduced susceptibility is found.

A more recent theory proposes that NaCl and water react to form NaOH and HCl. The HCl reacts with the protective oxides on the surface, forming unprotective chlorides. The hydrogen released by the attack of the exposed titanium is then believed to diffuse into the metal to cause subsequent hydrogen embrittlement.

It appears that most titanium alloys are susceptible to some degree to hot-salt stress-corrosion cracking. The alpha-phase alloys, such as Ti-5Al-2.5Sn, Ti-7Al-12Zr, and Ti-5Al-5Sn-5Zr, are apparently most susceptible to attack. The alpha-beta alloys are less susceptible, and the degree of susceptibility may increase with increases in aluminum content. For example, the Ti-8Al-1Mo-1V alloy (both as mill annealed and duplex annealed) is very susceptible. However, the Ti-8Mn alloy, which contains no aluminum, is also susceptible.

Alloys with intermediate resistance are Ti-5Al-5Sn-5Zr-1Mo-1V, Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-5Al-2.75Cr-1.25Fe, and Ti-3Al-11Cr-13V. Among the most resistant alloys are Ti-4Al-3Mo-1V, Ti-2.5Al-11Sn-5Zr-1Mo-0.2Si, and an experimental Ti-2Al-4Mo-4Zr alloy. Variations in heat treatment have been found to affect the reactivity of many alloys. Table 1-0.5.2.2-1 lists approximate stress-temperature thresholds for several titanium alloys.

The use of certain coatings on a titanium surface shows promise of protection. Surface coatings of nickel plate, aluminum plate, and zinc plate show promise of delaying attack when the coating is nonporous. In one study, flame-sprayed aluminum and nickel and electroless nickel were porous and not very effective, while hot-dipped aluminum gave good protection. In other work, promising results were obtained with a duplex nickel coating. In view of the role of oxygen (even as TiO_2) on the hot-salt cracking, it is not believed that anodized films will offer satisfactory protection.

Another phenomenon that is closely related to stress-corrosion cracking is that of liquid-metal embrittlement.[13] Many alloy systems, including titanium, have been found to exhibit brittle failure when in contact with specific low-melting-point metals.[22] In the case of titanium alloys, molten cadmium will cause cracking. Mercury and mercury amalgams also initiate cracking. However, in this case, plastic rather than elastic deformation is required to induce cracking. More recently, it has been found that silver will cause cracking of stressed Ti-7Al-4Mo and Ti-5Al-2.5Sn alloys at temperatures of 650 F and above.

1-0.5.2.3 Galvanic Corrosion

In most environments, the potential of passive titanium is quite similar to that for Monel and stainless steels.[23] Therefore, galvanic effects are not likely to occur when titanium alloys are coupled to these materials. On the other hand, less noble materials, such as aluminum alloys, carbon steels, and magnesium alloys, may suffer accelerated attack when coupled with titanium.[24] The extent and degree os such galvanic attack depends upon the relative areas of the titanium and the other metal. For example, where the area of the anodic material is small in relation to that of titanium, severe corrosion of the anodic material will occur. On the other hand, less attack will be evident if the areas of the two metals are reversed

TABLE 1-0.5.2.2-1. APPROXIMATE THRESHOLDS FOR STRESS-CORROSION CRACKING OF TITANIUM ALLOYS IN HOT SALT[17]

		100-Hr Threshold Stress, ksi								
	Condition	550	600	650	700	750	800	850	900	950
Ti-4Al-3Mo-1V	Aged	--	95	--	35	--	25	--	--	--
	Annealed	84	78	--	28	--	15-49	--	--	--
Ti-2.5Al-1Mo-10Sn-5Zr	Aged	--	--	--	70	--	40	--	35	--
Ti-5Al-5Sn-5Zr-1Mo-1V		69	--	--	--	--	35	--	--	--
Ti-6Al-4V	Aged	--	95	65	25	30	12	15	--	--
	Annealed	50	50	--	22	--	18-24	--	--	--
Ti-5Al-2.75Cr-1.25Fe	Aged	--	80	--	25	--	16	--	--	--
	Annealed	--	45	--	--	--	15	--	--	--
Ti-8Al-1Mo-1V	Aged	--	--	--	--	25	--	20	--	15
	Annealed	25	55	--	23	--	18	--	--	--
Ti-5Al-2.5Sn	Annealed	28	30	--	15	--	10-20	--	--	--
Ti-7Al-12Zr		--	--	--	--	--	<5	--	--	--
Ti-5Al-5Sn-5Zr		--	--	--	--	--	<5	--	<5	--

Such attack can be prevented or minimized in most cases by protective paints and other treatments, which include modifying the environment or insulating the dissimilar metals from direct contact with each other.

1-0.5.2.4 Crevice Corrosion

Crevice corrosion of titanium and its alloys has been shown to occur in chloride-salt solutions at elevated temperature.[25] This attack occurs above 200 F, with increasing frequency from 300 to 400 F. Acid and neutral solutions cause the greatest susceptibility, whereas no attack has been observed at pH of 9 or more. Crevice attack occurs with about the same frequency among unalloyed titanium and the common titanium alloys. Only the titanium alloy with about 0.2 percent palladium provides increased resistance to crevice attack, but it too is attacked after long-term exposure at elevated temperature.

While the mechanism is not completely understood, microcrevices, lack of oxygen, and hydride formation may be involved.

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1-1 Unalloyed Titanium

1-1.0 GENERAL REMARKS

The term unalloyed titanium is used to designate several grades ot titanium containing minor amounts of impurity elements such as carbon, oxygen, and iron. Three grades are described here as representative of the available unalloyed grades which are characterized by different yield strengths.

1-1.1 COMMERCIAL DESIGNATIONS

YS 40 ksi	YS 55 ksi	YS 70 ksi	Producer
A-40	A-55	A-70	Crucible Steel Co.
Carlson A	Carlson A	Carlson A	G. O. Carlson, Inc. [a]
HA-1940	HA-1950	HA-1970	Harvey Aluminum Co.
--	--	MET-RMD-2	Misco Division, Howmet Corp. [a]
--	OMC-105	--	Oregon Metallurgical Corp. [a]
RMI-40	RMI-55	RMI-70	Reactive Metals, Inc.
Ti-55A	Ti-65A	Ti-75A	Titanium Metals Corp.

(a) Selected product forms available.

1-1.2 ALTERNATE DESIGNATIONS (Common Names)

Commercially pure, CP, or unalloyed

1-1.3 ALLOY TYPE

Essentially all alpha

1-1.4 COMPOSITION, RANGE OR MAXIMUMS, %

Element	YS~40 ksi	YS~55 ksi	YS~70 ksi
Carbon	0.10-0.20	0.20	0.20
Nitrogen	0.07	0.07	0.07
Iron	0.30	--	--
Oxygen	0.15	--	0.40
Hydrogen	0.015	0.015	0.0125
Manganese	0.20	--	--
Other total	0.60	0.60	0.80

1-1.5 SPECIFICATIONS

YS 40 ksi

AMS-4902
AMS-4941 & 4951
MIL-T-9046E Type I, (A)
MIL-T-12117, Class 50

YS 55 ksi

AMS-4900A
MIL-T-9406E, Type I, (C)
MIL-T-7993, Class II

YS 70 ksi

AMS-4901B
AMS-4921A
MIL-T-9046E, Type I, (B)
MIL-T-12117, Class 70
MIL-T-7993, Class I

1-1.6 DESCRIPTION AND METALLURGY

1-1.6.1 Composition and Structures

The oxygen, nitrogen, carbon, hydrogen, iron, manganese, and other elements in unalloyed titanium are mostly unintentional. The exception is oxygen, which is added to make the higher strength grades. This addition is made by selecting blends of the raw sponge titanium which have varied impurity (oxygen and other elements) content resulting from the variables of manufacture. If only high-purity sponge-titanium lots are available (low oxygen content), another method of making the higher strength grades of commercially pure titanium is to blend in portions of scrap that have known higher oxygen contents. In this way, the alloy content is controlled to result in the grade desired.

Oxygen, nitrogen, and carbon strengthen the base metal by forming interstitial solid solutions, resulting in essentially single-phase nonheat-treatable alpha alloys. Hydrogen is most commonly removed to insignificant levels during melting and, unless reintroduced by poor practice during subsequent processing and utilization, does not enter into the metallurgy of the unalloyed titanium grades. The beta stabilizers, iron and manganese, also are present in low amounts. However, enough of these elements are present.to cause occasional beta-phase stabilization, which is observable in the microstructure. Nevertheless, the beta phase so stabilized is present in such small amounts that it does not promote even the slightest heat-treatment response and has never been known to contribute to adverse properties after severe processing procedures or after severe service conditions.

The beta transus temperatures of three typical grades of unalloyed titanium are:

YS Grade, ksi	Transus Temperature, F
40	~ 1675
55	~ 1700
70	~ 1740

Because of the small amount of beta stabilizer content in the highest purity grades, the temperature range where alpha and beta phases are in

equilibrium is very narrow. Practically no differences in mechanical properties are found with acicular structures obtained by cooling from above the beta transus and equiaxed structures obtained by thermal history below the beta transus.

1-1.6.2 Deformation Practice and Effects

The unalloyed titanium grades are readily forged at the intermediate temperatures shown below:

YS Grade, ksi	Blocker	Finish
~ 40	1600-1700 F	1500-1600 F
~ 55	1600-1700 F	1500-1600 F
~ 70	1650-1700 F	1500-1600 F

Time at elevated temperature is kept at a minimum to reduce oxidation and grain growth. Slightly oxidizing atmospheres are used to minimize hydrogen pickup. Scale and contaminated surface layers should be removed after elevated-temperature operations. If these precautions are observed, good properties are easily obtained.

Unalloyed titanium grades work harden fairly rapidly when deformed at room temperature. The normal bending and forming operations afford no difficulties, however, if the deformation is limited to the uniform elongation of the material. There is a tendency for springback in bending operations that is sometimes overcome by warm-forming procedures (500 to 600 F). Additional information on the forming of unalloyed titanium is given in Section 3 of this handbook.

As supplied by the producers, mill-annealed unalloyed titanium grades are quite soft and ductile. Hardness values range grom 88 to 92 Rockwell B for the 40-ksi yield-strength grade, from 95 to 99 Rockwell B for the 55-ksi yield-strength grade, and from 23 to 29 Rockwell C for the 70-ksi yield-strength grade. Brinell hardness values (1500-kg load) range from 170 to 300 for the three grades. Bend ductilities range from about 1 to 2T for the 40-ksi yield-strength grade to about 2 to 3T for the highest strength for all grades. Because of this high inherent ductility, the unalloyed titanium grades can be used in cases where severe deformation is required for the manufacture of hardware. If reannealed after forming, the properties of unalloyed grades can be restored to those of the as-received material. If severe deformation is not followed by reannealing, property degradation might be experienced. Typically, after other than hot-working operations, tensile strength is increased and ductility is decreased. Cold-stretching operations can cause a loss in compressive yield strength of up to 25 percent.

1-1.6.3 Heat-Treatment Practice and Effects

1-1.6.3.0 General Remarks

Annealing heat treatments ranging between 1 hour at 1000 F up to 2 hours at 1300 F, followed by air cooling, are used to restore mill-annealed yield strength. The treatment selected depends upon the work introduced into the metal during forming and the degree of annealed strength restoration desired. Unalloyed titanium grades are not heat treatable to cause increases in strength levels.

1-1.6.3.1 Stress-Relief Annealing

Stress-relief treatments are those designed to partially remove or largely overcome the effects of residual stresses. The stress relieving temperatures will depend on the amount of strain induced in the material. Thus, where the degree of deformation is known and restoration of compressive yield strength is the objective, particular combinations of time and temperature can be used as shown by the following example:

Grade	Stretch, %	Annealing Time, min	Annealing Temp, F	Compressive YS Recovery, %
YS of 70 ksi	1-3	60	825	94
	1-3	15	1075	94

In practice, where the degree of deformation is not always known, or where the reduction of residual stresses to a low level is desired, a treatment of 15 to 30 minutes at 1000 to 1100 F is usually given for all unalloyed grades. The stress-relief annealing treatment is terminated by air cooling. Experimental stress-relief data obtained for the 55 ksi yield strength grade of unalloyed titanium are shown in Figure 1-1.6.3.1-1.

1-1.6.3.2 Annealing

For the complete removal of residual stresses or for obtaining optimum tensile ductility, higher temperatures than stress-relief annealing temperatures are used. Commonly, 2-hour exposure at 1300 F followed by air cooling is used for all unalloyed titanium grades. Higher temperatures are possible but are always dangerous from the standpoint of introducing excessive oxidation and contamination.

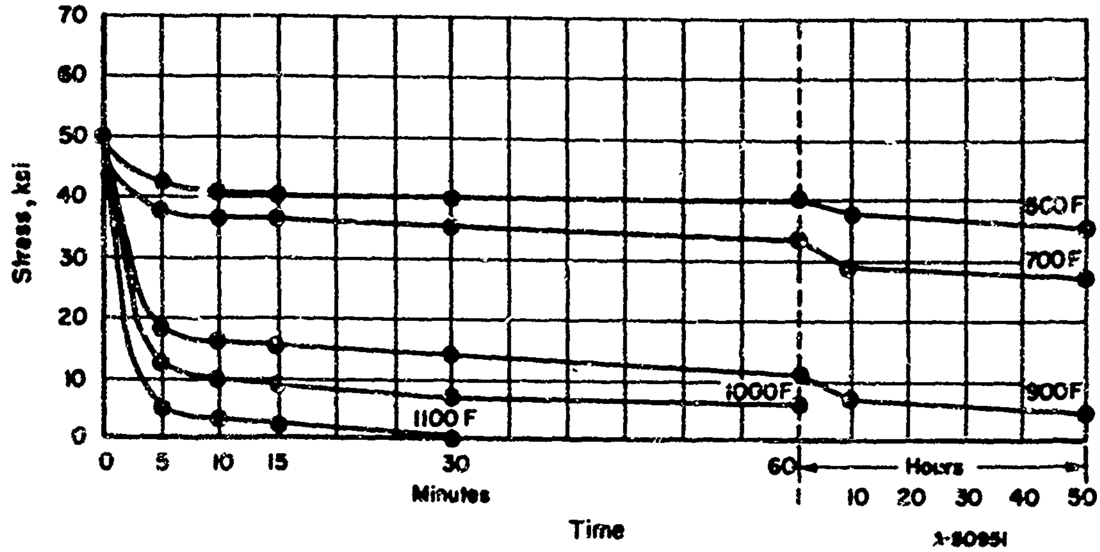

FIGURE 1-1.6.3.1-1. RELIEF OF RESIDUAL STRESS VERSUS TIME AT 500 F, 700 F, 900 F, 1000 F, AND 1100 F IN UNALLOYED TITANIUM (55-KSI YS)[1]

1-1.6.3.3 Strengthening Heat Treatments

The commercial grades of unalloyed titanium exist essentially as single-phase (alpha) solid-solution alloys over a wide range of temperatures and are not heat treatable to higher strength levels.

1-1.6.4 Stability

1-1.6.4.1 Thermal Stability

Due to the single-phase nature of unalloyed titanium grades, no inherent instability phenomena are encountered. Grain size may be greatly affected by thermal exposure, depending largely upon the work history of the material as shown in Figure 1-1.6.4.1-1. However, within the usual and reasonable limits, no major changes in properties are observed that can be traced to thermal treatment.

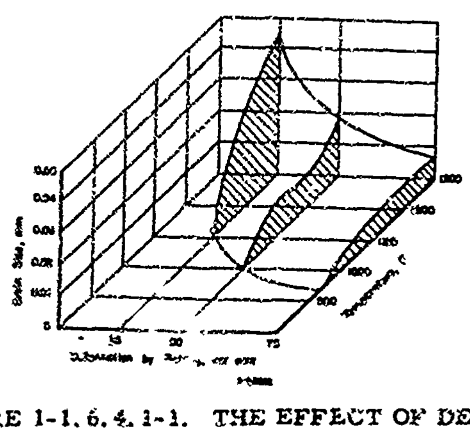

FIGURE 1-1.6.4.1-1. THE EFFECT OF DEFORMATION AND TEMPERATURE ON THE RECRYSTALLIZED GRAIN SIZE OF 0.022-INCH-THICK UNALLOYED TITANIUM[1]

1-1.6.4.2-1 Chemical Stability

The chemical reactivity of unalloyed titanium is described in the corrosion section (1-0.5). In general, titanium possesses outstanding corrosion resistance to most media at ambient temperatures. At elevated temperatures, the principal reactivity of concern is that between titanium and oxygen. Oxygen will react at quite low temperatures to form titanium oxide, first in invisible quantities, then through a spectrum of interference colors, and finally in quantities sufficient to be described as scale. Adjacent to the oxide layer, portions of the oxygen dissolve in the titanium and strengthen it by solid-solution mechanism.

The titanium-oxygen reactivity is time-temperature dependent. For example, short-time exposure in air at 750 F will hardly affect surface appearance, but with long-time exposure, a definite color change occurs. Color intensifies with increasing temperature until at temperature from 1000 F up, definite scale formation is observed, color and thickness depending on exposure time and surface condition.

Oxygen contamination beneath the visible oxide layers on titanium is negligible at temperatures below about 1000 F. As measured by a hardness increase in the subscale metallic layers, contamination increases with increasing temperature. This is illustrated by the data given in Figure 1-1.6.4.2-1. In general, the scale and contaminated layer on titanium should be removed for optimum properties.

While stress corrosion may occur in commercially pure unalloyed titanium grades in some media, salt-stress corrosion (NaCl) of unalloyed titanium has never been reported. It is especially not apt to occur in service, since unalloyed titanium

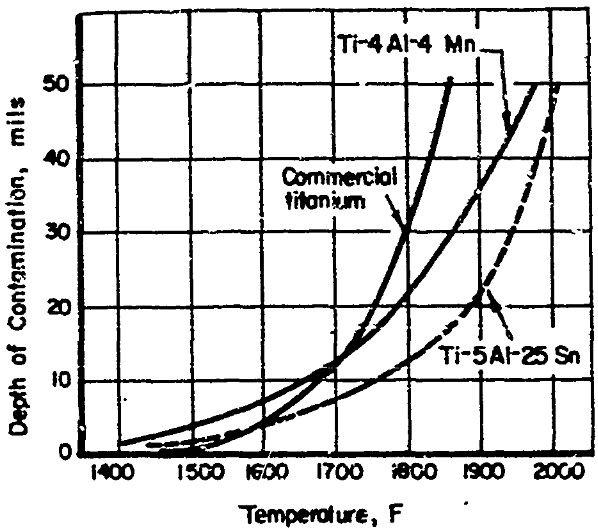

FIGURE 1-1.6.4.2-1. A COMPARISON OF THE CONTAMINATION OF COMMERCIAL TITANIUM, Ti-5Al-2.5Sn, AND Ti-4Al-4Mn AFTER A HYPOTHETICAL EXPOSURE OF 10 HOURS IN AIR[1]

The criterion of contamination for each alloy is a hardness increase of 75 Knoop points.

is not ordinarily used at elevated temperatures in moderately high stressed conditions. The usual precautions concerning avoidance of chloride containing compounds in processing should nevertheless be observed in order to maintain proper shop discipline regarding titanium-chlorine association.

1-1.7 REFERENCES

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1-2 Titanium Alloy Ti-5 Al-2.5 Sn

1-2.0 GENERAL REMARKS

Two grades of this alloy are made. The standard grade is described here. A higher purity grade designated ELI, for extra-low-interstitial (impurity) content, is designed for cryogenic usage where high toughness is required.

1-2.1 COMMERCIAL DESIGNATIONS

Designation	Producer
A-110AT	Crucible Steel Company
HA-5137	Harvey Aluminum Company
MET-RMD-3	Misco Division, Howmet Corporation
OMC-166A	Oregon Metallurgical Corporation
RMI-5Al-2.5Sn	Reactive Metals, Incorporated
Ti-5Al-2.5Sn	Titanium Metals Corporation

Forms Available[a]

B, b, P, W
B, b, E
Castings
B, castings
B, b, P, S
B, b, P, S, s, W, E

(a) B = billet, b = bar, P = plate, S = sheet, s = strip, W = wire, E = extrusions.

1-2.2 ALTERNATE DESIGNATIONS (COMMON NAMES)

5 - 2-1/2, aluminum-tin alpha, A-110, IMI-317 (British)

1-2.3 ALLOY TYPE

All alpha

1-2.4 COMPOSITION, RANGE OR MAXIMUMS %

	Standard Grade	ELI Grade
	Major Elements	
Al	4.0-6.0	4.7-5.6
Sn	2.0-3.0	2.0-3.0
Fe	0.50	0.1-0.2
Mn	0.30	--
	Interstitial Elements	
O	0.20	0.12
C	0.15	0.08
N	0.07	0.05
H	0.003-0.020	0.0125 bar 0.0175 sheet

1-2.5 SPECIFICATIONS

AMS-4910 MIL-T-9046E
AMS-4926 MIL-T-9047C
AMS-4953
AMS-4966

1-2.6 DESCRIPTION AND METALLURGY[1]

1-2.6.1 Composition and Structure

The Ti-5Al-2.5Sn alloy is an all-alpha alloy with typical all-alpha good weldability and elevated-temperature strength, but lacking heat treatability. The small beta-stabilizer content (iron and manganese) is present as impurity and can be detrimental to extreme low-temperature properties. However, the beta content is usually so small as to be ineffective metallurgically except to cause enough beta-phase stabilization to be seen metallographically. The low-interstitial grade (ELI) which has a lower iron and manganese content does not show the beta-phase metallographically and is generally lower in strength than the standard grade.

The effects of adding tin to experimental titanium-5 percent aluminum alloys made from iodide- or a sponge-base titanium are shown in Table 1-2.6.1-1. The ELI grade of the 5Al-2.5Sn alloy is between the two examples of titanium purity used in this illustration. Here it will be noted that the increased strength of the commercial purity grade is obtained with essentially the same ductility. These data also indicate an apparent tolerance for interstitials, as no loss in tensile ductility is reported in the higher interstitial, sponge-base alloys, even though an appreciable increase in strength is obtained. While this is true at room and elevated temperatures, higher ductility is found with increasing purity at low temperatures.

TABLE 1-2.6.1-1. COMPARISON OF LABORATORY HEATS OF HIGH-PURITY AND COMMERCIAL-PURE ALPHA ALLOYS[a][1]

Property	High Purity	Commercial Purity	High Purity	Commercial Purity
TS, ksi	65	105	95	120
0.2% Offset YS, ksi	60	95	80	110
RA, %	40	40	40	40
El, % in 1 in.	20	20	20	20
Min Bend Radius, T	1.5	2.0	1.5	2.5

(a) 0.040-inch sheet, annealed at 850 C (1560 F).

The microstructures observed in 5Al-2.5Sn alloy are relatively simple. The structure at room temperature is essentially all alpha. However, traces of beta phase are usually found, resulting from stabilization of this phase by the residual iron content of the sponge. The alpha will have two basic forms: equiaxed and acicular. The equiaxed alpha structure is obtained by mechanical working and subsequent annealing at temperatures in the alpha-phase field. The alpha to alpha-beta transus temperature is about 1875 F, and all-beta structures are found above about 1925 F.

The acicular alpha results from cooling from the beta-phase region. The cooling rate may alter the appearance of this type of structure. Water quenching produces the typical sharp acicular, martensitic alpha structure. Furnace cooling from the beta-phase region, on the other hand, produces a large, rounded acicular alpha-grain structure. The microstructures above are the result of extremes in cooling rate, and intermediate cooling rates will alter the size and shape of the alpha grains. In addition, the size of the prior beta grains may be altered by time and temperature of holding in the beta field prior to cooling.

1-2.6.2 Deformation Practice and Effects[2]

Suggested forging temperatures for the Ti-5Al-2.5Sn alloy range from 1650 to 2150 F. However, forging above the beta-transus temperature is suggested only for particularly severe deformation on thick section material and should be limited and followed by deformation at lower temperatures. The more common forging temperatures suggested by two sources are shown below.

Blocking Temperature, F	Finishing Temperature, F
1700-2000	1775-1850
1850-1900	1650-1850

All other fabrication and forming temperatures are substantially lower. Thus, with the exception of some forging operations, fabrication of Ti-5Al-2.5Sn is conducted with the alloy in the all-alpha conditio Alpha titanium is appreciably more resistant to idation than beta titanium.

There are two side effects of forming operations that should be recognized. One is the decrease in compression yield strength after tension deformation, called the Bauschinger effect. The second is the possibility of air contamination during heating for forming or heat treatment, which results in decreased ductility of the material. While warm forming may be used to facilitate fabrication, it does not eliminate the Bauschinger effect, and if the elevated-temperature exposure is for a long time at temperatures above about 1200 F, contamination may become a larger problem than the difficulty of forming. To illustrate these forming effects on mechanical properties, Table 1-2.6.2-1 is used to show Bauschinger effects, while Table 1-2.6.2-2 is used to show the effect of contamination on bend ductility. Table 1-2.6.2-3 shows that there is little advantage in using very high temperature for forming, since the principal increase in bend ductility is achieved in temperatures up to 1000 F.

The 5Al-2.5Sn alloy, while not heat treatable, is strengthened by cold work, as shown by the data in Table 1-2.6.2-4 for bar stock cold drawn to a 15 percent reduction in area.

TABLE 1-2.6.2-3. EFFECT OF TEMPERATURE ON MINIMUM BEND RADIUS OF Ti-5Al-2.5Sn ALLOY[1]

Test Temperature, F	Bend Radius to Thickness Ratio: Longitudinal	Bend Radius to Thickness Ratio: Transverse
RT	4.0-4.5	4.0-4.5
400	3.5-4.0	3.5-4.5
800	2.0-3.0	2.5-3.0
1000	1.5-2.5	2.0-2.5
1200	1.0-2.0	1.0-2.0

TABLE 1-2.6.2-4. COMPARISON OF TENSILE PROPERTIES OF ANNEALED AND COLD DRAWN Ti-5Al-2.5Sn ALLOY[1,3,4]

	Annealed	Cold Drawn 15 Percent
UTS, ksi	142.5	175.0
0.2% Offset YS, ksi	127.5	151.0
Proportional Limit, ksi	122.5	75.0
El, % in 2 in.	17.0	10.0
RA, %	39.0	28.0
Elastic Modulus, 10^6 psi	15.7	14.4
Type of Fracture	Flat 1/2 cup	Flat 1/2 cup

Material strengthened by cold working would, of course, be limited in the range of temperature in which it could be used. The lower temperature for recovery on recrystallization would be the upper limit of service temperature for cold-worked material. The maximum service temperature would decrease for increased amounts of cold work, but appears to be about 700 F for 15 percent cold work.

TABLE 1-2.6.2-1. TYPICAL MECHANICAL PROPERTIES OF AS-RECIEVED, STRETCHED, AND STRESS-RELIEVED Ti-5Al-2.5Sn TITANIUM ALLOY(1, 2, 3, 4)(a)

Specimen Description	Compressive Yield Strength (0.2% Offset) ksi	Tensile Yield Strength (0.2% Offset) ksi	Tensile Ultimate Strength, ksi	Elongation, % in 2 inches	Percentage of As-Received Compressive Yield Strength
As received	129.9	121.7	131.8	19.8	100
1% Stretch					
As stretched	87.8	125.6	131.9	20.0	67.6
Stress relieved	122.8	121.5	131.6	21.0	94.5
3% Stretch					
As stretched	84.9	131.7	135.9	18.3	65.4
Stress relieved	121.5	120.7	133.0	17.5	93.5

(a) These are not design allowables.

TABLE 1-2.6.2-2. EMBRITTLEMENT BEND-TEST RESULTS FOR Ti-5Al-2.5Sn(1)

Exposure Time, hours	Measurement	800 F A	800 F B	900 F A	900 F B	1000 F A	1000 F B	1200 F A	1200 F B	1400 F A	1400 F B	1500 F A	1500 F B	1600 F A	1600 F B	1700 F A	1700 F B	1800 F A	1800 F B
		Bend Angle or Bend Radius for Samples A and B at Indicated Temperature(a)																	
1	Angle, deg	180	180	180	180	180	180	180	180	65	60	65	75	50	35	20	30	10	5
	MBR, T	2.3	2.2	2.3	2.3	2.3	3.0	1.1	2.2	--	--	--	--	--	--	--	--	--	--
2	Angle, deg	180	180	180	180	180	180	180	180	65	55	65	55	35	45	5	25	0	3
	MBR, T	2.3	2.4	2.2	2.4	2.2	2.6	1.2	2.2	--	--	--	--	--	--	--	--	--	--
5	Angle, deg	180	180	180	180	180	105	180	180	55	45	65	50	20	25	0	15	0	0
	MBR, T	2.4	2.2	2.6	2.6	2.3	--	2.2	2.2	--	--	--	--	--	--	--	--	--	--
10	Angle, deg	180	180	90	180	180	180	105	180	50	40	50	40	5	5	0	--	--	--
	MBR, T	2.4	2.5	--	2.8	2.5	2.8	--	2.5	--	--	--	--	--	--	--	--	--	--
20	Angle, deg	180	180	180	85	145	115	70	55	45	45	35	30	0	0	--	--	--	--
	MBR, T	1.9	2.4	2.9	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
50	Angle, deg	180	180	70	180	75	75	60	50	30	40	30	30	0	0	--	--	--	--
	MBR, T	2.3	2.8	--	2.9	--	--	--	--	--	--	--	--	--	--	--	--	--	--
100	Angle, deg	180	180	70	85	90	75	50	45	25	20	--	--	--	--	--	--	--	--
	MBR, T	2.2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
200	Angle, deg	180	180	70	85	70	65	35	35	30	25	--	--	--	--	--	--	--	--
	MBR, T	2.1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
500	Angle, deg	65	95	55	65	55	85	30	30	0	10	--	--	---	--	--	--	--	--

(a) Values listed are either the bend angle over a 3.3T radius in degrees or the minimum radius in terms of T for a 180-degree bend. A and B samples received identical treatment.

Relaxation tests on bar stock of 5Al-2.5Sn alloy gave the results in Table 1-2.6.2-5 for tests at 700 and 800 F. These data indicate a definite loss of creep resistance at 800 F for the cold-worked material.

1-2.6.3 Heat Treatment Practice and Effects

1-2.6.3.0 General Remarks

Since the Ti-5Al-2.5Sn alloy is single-phase alpha type, heat treatment is confined to stress relief or full annealing treatments.

1-2.6.3.1 Stress-Relief Annealing[2]

The stress-relief annealing of this alloy is usually accomplished in the 1000 to 1200 F temperature range at times between 15 minutes and 1 hour and is followed by air cooling. As shown by the data in Figure 1-2.6.3.1-1, very little relaxation takes place in 700 F exposure, only part of the residual stresses can be relieved in practical exposure time at 900 F, and significant stress-relief annealing can be accomplished in 1 hour at 1100 F. Shorter times at higher temperatures may also be used with the usual precautions against contamination being followed. Depending upon the condition of the material and the required condition with respect to residual stress, a time-temperature combination can be selected to meet the mechanical properties desired.

1-2.6.3.2 Annealing

The full annealing of Ti-5Al-2.5Sn alloy may be accomplished by thermal exposure in the range 1300 to 1600 F for times between 15 minutes and 4 hours. The shorter times are used at the higher temperatures. Cooling rate from this temperature range has little effect on properties. Air cooling is usually used for convenience. Furnace cooling might be required in vacuum annealing for example.

Temperatures above 1600 F are seldom used for annealing the Ti-5Al-2.5Sn alloy, since problems in excessive grain growth and oxidation can be encountered. Annealing in the preferred alpha temperature range imparts or restores the optimum ductility and toughness to the alloy.

Heating into the beta field without subsequent working in the alpha field causes a loss of ductility in room-temperature tensile tests with little effect on strength. This is shown in Table 1-2.6.3.2-1 for 5Al-2.5Sn material extruded at 1700 F. Slow cooling from the beta field (2100 F) produces the relatively low ductility of about 8 percent elongation and 15 percent reduction of area. Quenching from the beta field increases the ductility to 12 percent elongation and 25 percent reduction of area, whereas annealing in the alpha field (1200 to 1850 F) produces about 17 percent elongation and 45 percent reduction of area.

1-2.6.3.3 Strengthening Heat Treatments

Because 5Al-2.5Sn alloy has essentially an all-alpha structure, it would be expected that heat treatment would have little effect on its mechanical properties. Early experience indicated that a small increase in strength could be achieved by solution treatment followed by aging, but in practice this treatment is never used.

1-2.6.4 Stability

1-2.6.4.1 Thermal Stability

Thermal stability measurements on the Ti-5Al-2.5Sn alloy made by comparing room-temperature properties before and after thermal exposure (stressed or unstressed) have indicated that this alloy is metallurgically stable under any conditions of stress, temperature, and time up to the annealing temperature.

The only changes in properties due to thermal exposure that have been observed are believed to be traceable to the relief of residual stresses. For example, tensile and fatigue specimens prepared from butt-fusion-welded sheet were found to change in strength and ductility after a 500-hour, 700 F exposure. After welding and before exposure, the specimens were stress-relief annealed for 30 minutes at 1200 F, furnace cooled to 1000 F, and air cooled. A fatigue-strength improvement of about 10 ksi (smooth specimens, 10^7 cycles) was found after 500 hours of exposure at 700 F. The tensile data are shown below.

	Yield Strength, ksi		El,
Condition	Compression	Tension	%
Before exposure	135	132	8
After exposure	135	131	10

1-2.6.4.2 Chemical Stability

The Ti-5Al-2.5Sn alloy possesses excellent corrosion resistance to most media and is somewhat more resistant to oxidation at temperatures up to 1000 F than alpha-beta alloys. Surface discolorations are found in as short a time as 1 hour in 800 F air exposure, but at 1000 F, scale build up does not occur on Ti-5Al-2.5Sn as early (>100 hours) as on such alloys as Ti-6Al-4V, Ti-8Mn, and Ti-2Fe-2Cr-2Mo. Above 1000 F, scale builds up in shorter times, but contamination beneath the scale is not a problem below 1500 F (see Figure 1-1.6.4.2-1).

The hot-salt-stress corrosion of Ti-5Al-2.5Sn alloy has been found to occur at 600 F and up in fairly short-time testing. Data from References

TABLE 1-2.6.2-5. RELAXATION OF Ti-5Al-2.5Sn AT 700 and 800 F[1,3,4]

Condition	700 F Initial Stress, ksi	700 F 500-Hour Stress, ksi	800 F Initial Stress, ksi	800 F 500-Hour Stress, ksi
Annealed	55.0	48.0	53.4	43.5
Cold Drawn Per Cent	55.2	48.0	53.2	35.0

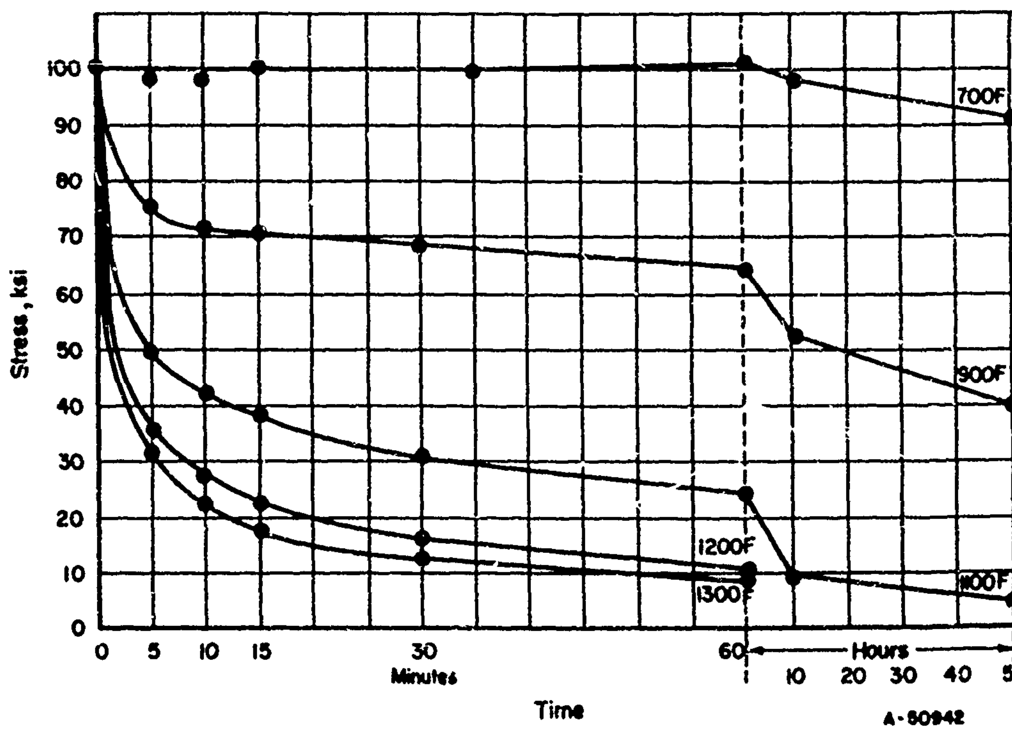

FIGURE 1-2.6.3.1-1. RELIEF OF RESIDUAL STRESS VERSUS TIME AT 700 F, 900 F, 1100 F, 1200 F, and 1300 F IN Ti-5Al-2.5Sn[2]

TABLE 1-2.6.3.2-1. TENSILE PROPERTIES OF ANNEALED 5Al-2.5Sn ALLOY EXTRUDED AT 1700 F (ALPHA-BETA EXTRUDED)[1]

Annealing Treatment	Tensile Strength Ultimate, ksi	Tensile Strength Yield, ksi	Elongation, % in 4D	Reduction of Area, %
2100 F, water quench	153 1	152.6	12.5	25.0
2100 F, air cool	149.0	138.8	8.3	15.2
2100 F, furnace cool	151.8	141.2	7.5	13.9
1850 F, water quench	146.3	131.4	16.7	50.0
1850 F, air cool	143.5	139.0	16.7	45.7
1850 F, furnace cool	144.2	141.2	15.5	43.7
1600 F, air cool	138.4	131.8	16.7	50.3
1200 F, air cool	146.0	143.2	16.7	43.4

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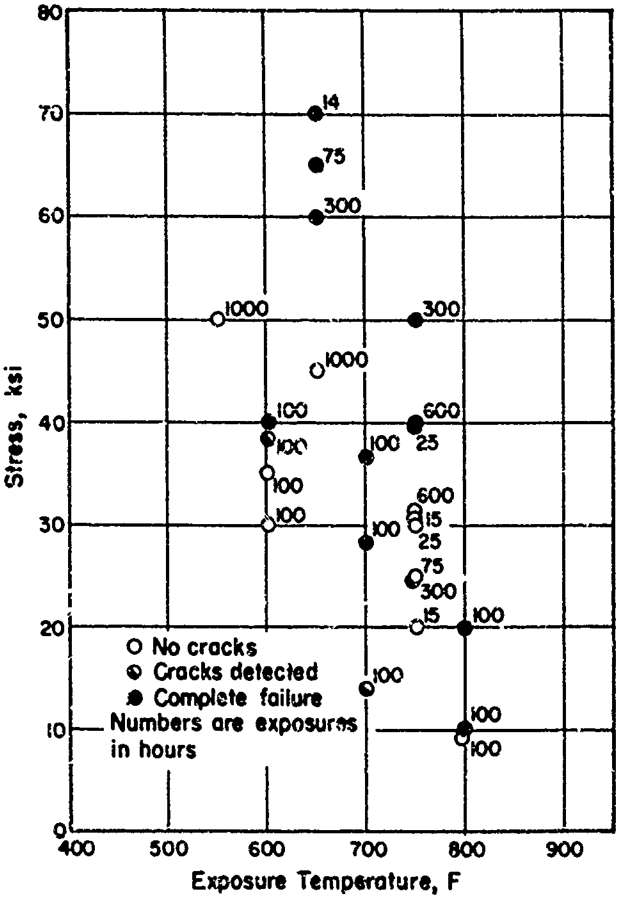


FIGURE 1-2.6.4.2-1. EFFECT OF EXPOSURE VARIABLES ON THE OCCURRENCE OF VISIBLE SALT-STRESS CORROSION IN Ti-5Al-2.5Sn ALLOY(5,6)

(5) and (6) are summarized in Figure 1-2.6.4.2-1 that also show the dependence of stress for the titanium salt reaction. However, the data are sparse for this alloy, and those data available do not clearly define time, temperature, and stress variables that are required to cause the degradation of properties. It is quite evident too, however, that Ti-5Al-2.5Sn is very susceptible to salt-stress corrosion. Work at Douglas Aircraft Company(6) identified this alloy as the most susceptible when compared with Ti-8Al-1Mo-1V, Ti-6Al-4V, Ti-4Al-3Mo-1V, and Ti-5Al-4FeCr compositions.

1-2.7 REFERENCES

(1) Robinson, H. A., "Compilation of Available Information on Ti-5Al-2.5Sn Alloy", TML Memorandum 126, Battelle Memorial Institute, Columbus, Ohio (July, 1957).

(2) Maykuth, D. J., "Stress Relief, Annealing, and Reactions with Atmosphere of Titanium and Titanium Alloys", TML Memorandum 118, Battelle Memorial Institute, Columbus, Ohio, (May, 1957).

(3) Gillig, F. J., Cornell Aeronautical Laboratory reports on stress relief and relaxation behavior of titanium, WADC TR 55-410, August, 1956, and WADC TR 55-458 (December, 1956).

(4) Sticha, E. A., "Relaxation Behavior of Titanium Alloys", WADC TR 55-458, Parts I and II, 1955.

(5) Body, W. K., and Fink, F. W., "The Phenomenon of Hot-Salt Stress-Corrosion Cracking of Titanium Alloys", NASA Report NASA CR-117 (October, 1964).

(6) "Chloride Stress Corrosion Susceptibility of High Strength Stainless Steel, Titanium Alloy, and Superalloy Sheet", ML-TDR-64-44, Volume II (May, 1964). Prepared by the Douglas Aircraft Company, Incorporated.

1-3 Titanium Alloy Ti-8Al-1Mo-1V

1-3.0 GENERAL REMARKS

The Ti-8Al-1Mo-1V alloy was first developed as a "super" alpha alloy for engine use, principally as forgings. Only one grade is produced that is essentially a high-purity grade and is now available in forgings, plate, sheet, bar, wire, and extruded forms.

1-3.1 COMMERCIAL DESIGNATIONS

Designation	Producer	Forms Available[a]
HA-8116	Harvey Aluminum Co.	B, b, E, W
No designation	Oregon Metallurgical Corp.	B
RMI-8Al-1Mo-1V	Reactive Metals, Inc.	B, b, P, S, E
Ti-8Al-1Mo-1V	Titanium Metals Corp.	B, b, P, S, s, W, E

(a) B = billet, b = bar, P = plate, S = sheet, s = strip, W = wire, E = extrusions.

1-3.2 ALTERNATE DESIGNATIONS (COMMON NAMES)

8-1-1 8Al super-alpha

1-3.3 ALLOY TYPE

Near alpha, alpha-beta

1-3.4 COMPOSITION RANGE OR MAXIMUMS, %

Major Elements		Interstitials	
Aluminum	7.5-8.5	Carbon	0.08
Molybdenum	0.75-1.25	Nitrogen	0.05
Vanadium	0.75-1.25	Oxygen	-- (~ 0.12)
Iron	--	Hydrogen	0.015 (sheet and plate) 0.0125 (bar) 0.0100 (billet)

1-3.5 SPECIFICATIONS

AMS-2241
AMS-2242
AMS-2249
MIL-T-9046F Type II (Comp. F)

1-3.6 ALLOY DESCRIPTION AND METALLURGY

1-3.6.1 Composition and Structure

The Ti-8Al-1Mo-1V alloy contains a relatively large amount of the alpha stabilizer, aluminum, and a fairly small amount of the beta stabilizers, molybdenum and vanadium (plus iron as an impurity). Although this alloy is metallurgically an alpha-beta alloy, the small amount of beta stabilizer in this grade (1Mo + 1V) permits only small amounts of the beta phase to become stabilized. Thus, the alloy is also properly known as a near-alpha alloy. Although it has some alpha-beta characteristics such as a mild response to heat treatment to increase strength, and microstructures show the presence of beta phase after alpha-beta thermal exposure, the alloy maintains several alpha-alloy characteristics such as good elevated-temperature creep strength and good weldability.

The beta to alpha-beta transus of the Ti-8Al-1Mo-1V alloy is approximately at 1900 F in material having normal interstitial content. In a recent study on the metallography of Ti-8Al-1Mo-1V[1], work on the phase relationships in this alloy indicated that the beta-phase transforms to martensite at temperatures in the alpha-beta field from the transus down to about 1650 F. Below this temperature, the beta phase is sufficiently enriched in molybdenum and vanadium to be retained, as shown by the X-ray-diffraction data below.

Quench Temperature, F	Percent Retained Beta
2200	<1
2100	2
2000	<1
1900	2
1800	<1
1700	<2
1600	16
1500	14

In another study[2], it was found that the martensite formed at elevated temperatures decomposes to form alpha plus beta structures upon tempering. In the same study, it was found that the beta phase decomposes during tempering at temperatures below about 840 F. Below about 970 F, the alpha phase undergoes a metallurgical reaction resulting in an ordered structure (DO_{19} type superlattice) of the same kind found in binary titanium-aluminum alloys. It has been suggested that the presence of the ordered structure is responsible for the differences in mechanical properties between duplex and mill-annealed material.

1-3.6.2 Deformation Practice and Effects

The practices used to convert ingots to mill products of Ti-1Al-1Mo-1V alloy usually result in a mixed two-phase alpha-beta structure. Fabrication and heat-treatment schedules involving temperatures above the beta transus temperature are not recommended because of the possibility of surface embrittlement in service conditions involving temperatures above 850 F[3]. However, initial metal working above 1900 F is safely done if followed by considerable deformation at

temperatures below the beta transus. Further, certain primary fabrication operations, such as extrusion, appear to result in good combinations of properties even though deformation is accomplished in the beta field. Nevertheless, unless for the development of some particular property or as necessitated by some fabrication process, the beta working of Ti-8Al-1Mo-1V alloy is avoided. Working at temperatures high in the alpha-beta field is the usual practice.

Sheet-metal-working temperatures (secondary fabrication) range downward from about 1450 F. The common range is 1200 to 1450 F. Lower temperatures than 1200 F are used too with appreciable forming possible even as low as room temperature. The Ti-8Al-1Mo-1V alloy has a bend ductility of 3 to 5 T, MBR (bend radius divided by thickness) at room temperature.

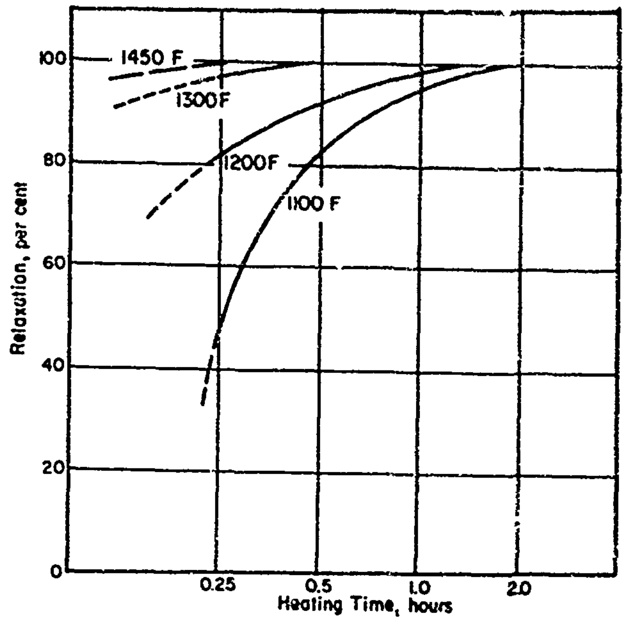
1-3. 6. 3 Heat Treatment Practice and Effects

1-3. 6. 3. 0 General Remarks

A wide variety of heat-treatment conditions are possible with the Ti-8Al-1Mo-1V alloy. A particular condition is usually selected on the basis of part section size, fabrication history, utilization environment, and the mechanical properties desired. Thick section product for engine use may be most desirable in a condition having maximum creep strength for example, while a strut forging may need to have good toughness at the sacrifice of a little strength, and a sheet part might end up in a heat-treated condition that was most producible. Thick section product may be heat-treated in the same way as thin section products, but properties are likely to differ because of differences in fabrication history and the effects of section size on cooling rates. Some heat treatments possible are very seldom if ever used.

1-3. 6. 3. 1 Stress-Relief Annealing

For Ti-8Al-1Mo-1V material that contains residual stresses resulting from cold forming, warm forming, or welding, it is useful to relieve these stresses by annealing. Stress-relief annealing treatments should consist of thermal exposures that do not disturb the metallurgical stability of the Ti-8Al-1Mo-1V alloy. Annealing data have been generated between 1100 and 1450 F. It was found that in about 2 hours at 1100 F to about 15 to 20 minutes at 1450 F, complete relaxation occurred, as shown in Figure 1-3. 6. 3. 1-1. Differences in cooling from the stress-relief annealing temperatures, especially if temperatures on the high side of the range are used, may significantly affect mechanical properties. When stress-relief annealing at 1400 to 1450 F, it is possible to control the annealed properties by thermal exposure conditions - mill and duplex annealed.



FIUGRE 1-3. 6. 3. 1-1. EFFECTS OF HEATING TIME AND TEMPERATURE ON THE RELAXATION OF RESTRAINED BEND SPECIMENS OF MILL-ANNEALED Ti-8Al-1Mo-1V SHEET(4,5)

0. 056-inch sheet mill annealed at 1450 F for 8 hours, then cold worked.

1-3. 6. 3. 2 Annealing

Annealing heat treatments for thick section product are usually of the duplex type involving solid-solution equilibration at temperatures between 1650 and 1850 F followed by stabilization annealing between 1100 and 1375 F. This kind of treatment has been found to result in good creep strength for applications such as turbine wheels and blades.

In the case of small section size product such as sheet, production is usually accomplished by fabrication in the alpha-beta field. This is followed by mill annealing for about 8 hours at 1400 to 1450 F (typical). Because mill annealing is usually done on large quantities of material at one time, large furnaces are used and furnace cooling from the annealing temperature is slow. Duplex annealing is simply a superimposition of another 1/4-hour, 1400 to 1450 F treatment on mill-annealed product, but the duplex-annealing treatment is terminated by air cooling (fast) rather than furnace cooling (slow). Thick-section, flat-rolled products also can be supplied in the mill-annealed and duplex-annealed conditions described above for sheet.

joining operations may require reannealing to regain the properties inherent in as-received metal. This in effect may be a step beyond stress-relief annealing, although it may be accomplished in much the same way. Further, creep forming may be incorporated in the reannealing treatment at temperatures starting from about 1450 F. In the above cases, longer exposure time followed by slow cooling (at about 100 F per hour from 1450 to 900 F) results in the mill-annealed condition. Twenty minutes' exposure followed by faster cooling (1450 to 900 F in less than 1 hour, i.e., air cooling quite satisfactory) results in the duplex-annealed condition. Intermediate cooling rates result in mechanical properties which are intermediate to those of mill- and duplex-annealed material. The effect of cooling rate on tensile properties is shown in Figure 1-3.6.3.2-1[6]. Material that has been cooled at a faster rate is not quite so strong as mill-annealed metal, but is tougher, as shown below.

Condition	UTS[a], ksi	TYS[a], ksi	El [a], %	Ratio of NTS to YS	Fracture Toughness (K_c), ksi√in.
Mill annealed	145	135	8-10	0.55	138
Duplex annealed	135	125	8-10	0.95	250

(a) Guaranteed minimums.

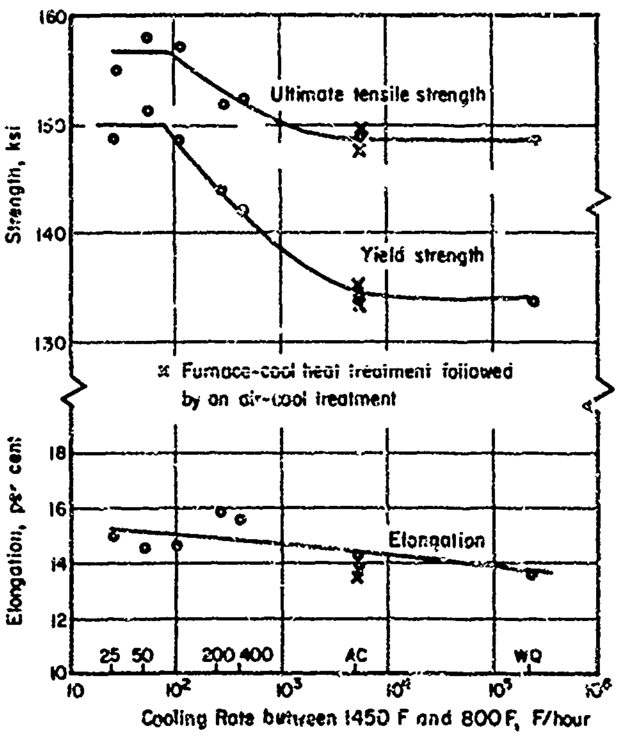


FIGURE 1-3.6.3.2-1. EFFECT OF COOLING RATE ON THE TENSILE PROPERTIES OF Ti-8Al-1Mo-1V SHEET[6]

Cooled from 1450 F after heating 8 hours

An annealed condition called a triplex annealed condition is available for Ti-8Al-1Mo-1V sheet and plate products also. To put the material into this condition, the producer reheats mill-annealed material to 1850 F, holds there a short time (about 5 minutes), and air cools the material to room temperature. The above high-temperature treatment, which is something like a solution heat treatment, is followed by reheat treatment at 1375 F for 15 minutes and is then air cooled. The 1375 F treatment is a short-time, high-temperature aging treatment[7]. The mechanical properties of the triplex-annealed condition are much like those of the duplex-annealed condition -- lower strength than mill annealed, but better fracture toughness -- and at least one investigation has shown that the resistance to salt-stress corrosion of triplex-annealed material is as good as or better than duplex-annealed material. Nevertheless, the triplex-annealed condition is no longer popular. This is probably due to the lack of a clear-cut advantage for it and to the complexities of achieving it.

With the advent of continuous strip-rolled product, it is very possible that changes in mill-processing heat treatment and user heat-treatment techniques will be required.

1-3.6.3.3 Strengthening Heat Treatments

The Ti-8Al-1Mo-1V alloy may be strengthened by solution heat treatment followed by aging. Equilibration heat treatments from high in the alpha-beta field (1650 to 1850 F) followed by water quenching permit subsequent aging of the metastable beta phase stabilized at the solution temperature. Aging is usually accomplished at intermediate temperatures in the 900 to 1200 F aging-temperature range. However, solution heat treatment plus aging is not a popular choice for the treatment of Ti-8Al-1Mo-1V alloy.

1-3.6.3.3.1 Solution Annealing

As solution-heat-treatment temperatures are raised from a point above the annealing temperature up to about 1700 F, the effect on the structure is to stabilize an increasing amount of the beta phase. An increasing amount of beta phase in the structure permits increasing aging response.

1-3.6.3.3.2 Aging Heat Treatments

After solution heat treatment in the range of 1650 to 1850 F, aging occurs in as short a time as 1 hour at temperatures from 900 to 1200 F. Overaging is observed in as few as 2 to 3 hours when an aging temperature of 1200 F is used. However, overaging is not found at 1100 F in times up to 50 hours. Both 1100 and 1000 F appear to be acceptable aging temperatures. The effects of several combinations of solution and aging treatments are shown in the summary curves of Figure 1-3.6.3.3.2-1[8].

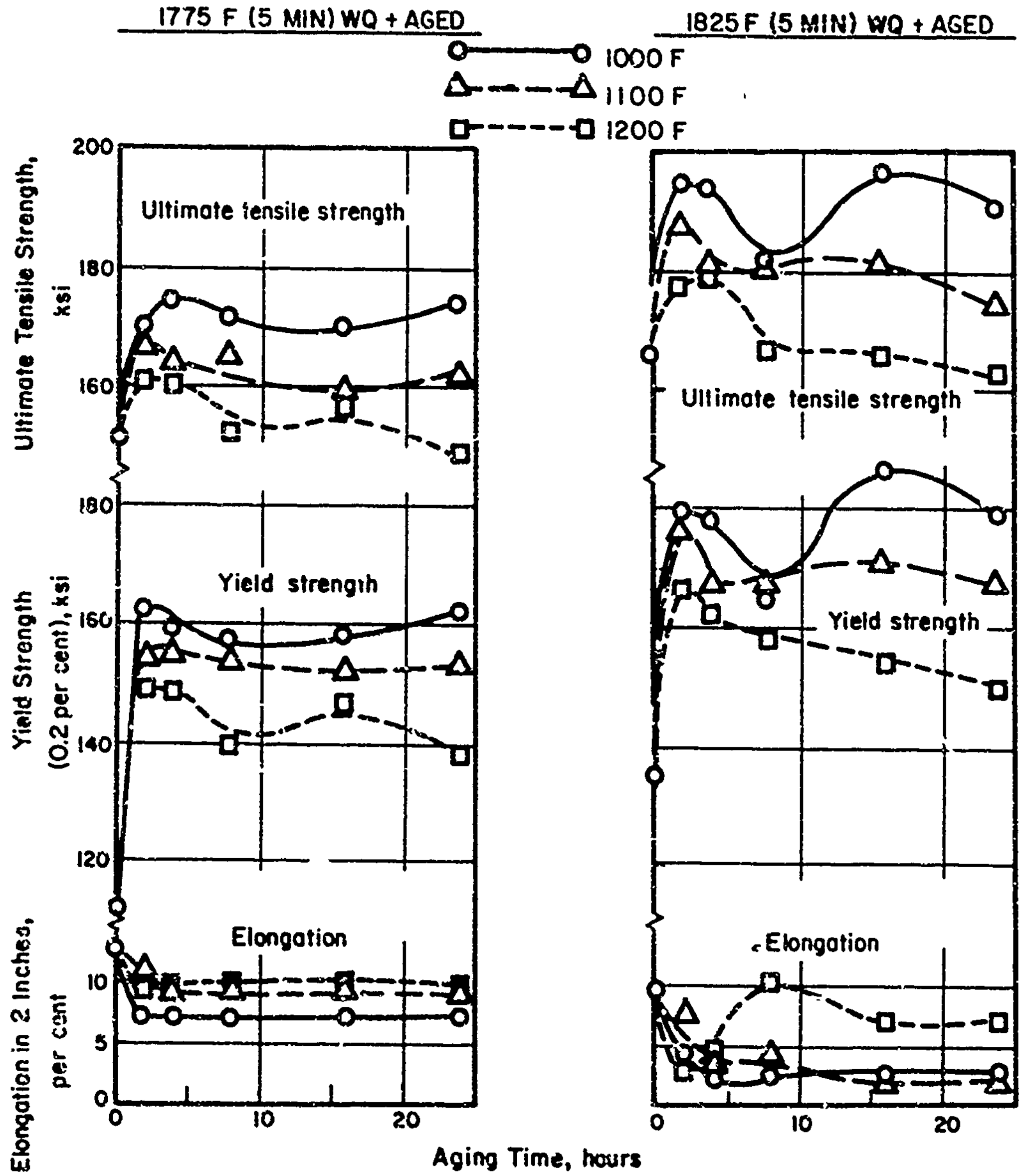


FIGURE 1-3.6.3.3.2-1. EFFECT OF AGING TIME AND TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF 0.020-INCH Ti-8Al-1Mo-1V SHEET SOLUTION TREATED AT 1775 F OR 1825 F[8]

1-3.6.4 Stability

The thermal stability and chemical stability of the Ti-8Al-1Mo-1V alloy are not well defined. Stability in this case is meant as no change in material characteristics as influenced by the exposure, which may or may not include a stress factor. Time, temperature, and stress, and, in addition, chemical environment or chemical stability, are known to be interrelated in their effects on structure and associated mechanical properties. In general, Ti-8Al-1Mo-1V alloy has been shown to be reasonably stable, as would be expected on the basis of alloy chemistry. Under certain conditions, however, significant degradation of mechanical properties has been observed. Intensive study of these conditions is still in progress.

1-3.6.4.1 Thermal Stability

Research-and-development work on very early material (1959) established that thermal stability was quite dependent on fabrication history, heat treatment, and exposure conditions. Selected tensile and creep-stability results are given in Table 1-3.6.4.1-1 that illustrate the effect of several variables including fabrication history, heat treatment, and exposure temperature and stress[8]. Table 1-3.6.4.1-2 shows the interrelated effects of time and stress at 950 F exposure on a single condition[9].

More recently, somelonger time tests have been used to determine the effects of thermal exposure on the properties of current Ti-8Al-1Mo-1V products namely mill-annealed and duplex-annealed sheet. Many of the tests, after exposures at temperatures in the range expected to be achieved in future aircraft, have shown no degradation of properties under some rather severe conditions in quite long times (up to 22,000 hours). Other exposure tests have indicated that properties may change significantly. Some of the exposures and test results that have been conducted are summarized in Table 1-3. 6. 4. 1-3[10]. The results of a series of tests conducted at The Boeing Company are summarized in Table 1-3. 6. 4. 1-4[5].

While it is quite clear that most of the changes in properties are small after exposures involving relatively low temperatures, stresses, and long times, the trend of property degration is equally clear. It appears likely that the changes are a result of the ordering reaction (see 1-3. 6. 1) occurring in these exposures. The extent of property degradation as a result of the relatively low temperatures and stresses after very long times (30 to 50,000 hours) is not known, and it is doubtful that it can be accurately predicted based on data presently available.

1-3. 6. 4. 2 Chemical Stability

The Ti-8Al-1Mo-1V alloy has essentially the same corrosion resistance as all titanium alloys to most organic salts and acids. Also, resistance to oxidation and contamination has been found to be good. Surface discolorations appear in lengthy exposured to as low as 550 F and change color and texture as higher temperature, longer time, or more severe oxidizing environments are encountered. While definitive data are not available, it is believed that the properties of Ti-8Al-1Mo-1V alloy are relatively unaffected by the small amount of surface oxide formed during service at temperatures up to about 900 F. Of course, exposure time is a factor, and significant degradation may occur in very long-time exposures even at moderate temperatures.

The reactivity between titanium and chloride salts at elevated temperature in the presence of tensile stresses is termed salt-stress corrosion and results in the degradation of mechanical properties. As in the thermal reactivity of Ti-8Al-1Mo-1V, time, temperature, and stress are interrelated with respect to this aspect of the alloys' chemical stability. Under severe exposure conditions of time, temperature (~700 F), stress and chloride-ion environment, Ti-8Al-1Mo-1V alloy may fail catastrophically as a result of the reaction. The results of several investigations have indicated that Ti-8Al-1Mo-1V alloy is very sensitive to salt-stress corrosion compared with some other common titanium alloys. However, research is still in progress to determine the conditions under which salt-stress corrosion significantly degrades mechanical properties and to rate the sensitivity of Ti-8Al-1Mo-1V with other common alloys.

Figure 1-3. 6. 4. 2-1 is a summary of the 8-1-1 data given in Reference[11]. Based on these data, salt-stress corrosion cracks appear at all stress levels at temperatures of 750 F and up, but higher stresses appear to be required as exposure temperatures are lowered. Exposure-time effects are not clear, except that only a short time is required to produce corrosion if temperature and stress conditions are severe.

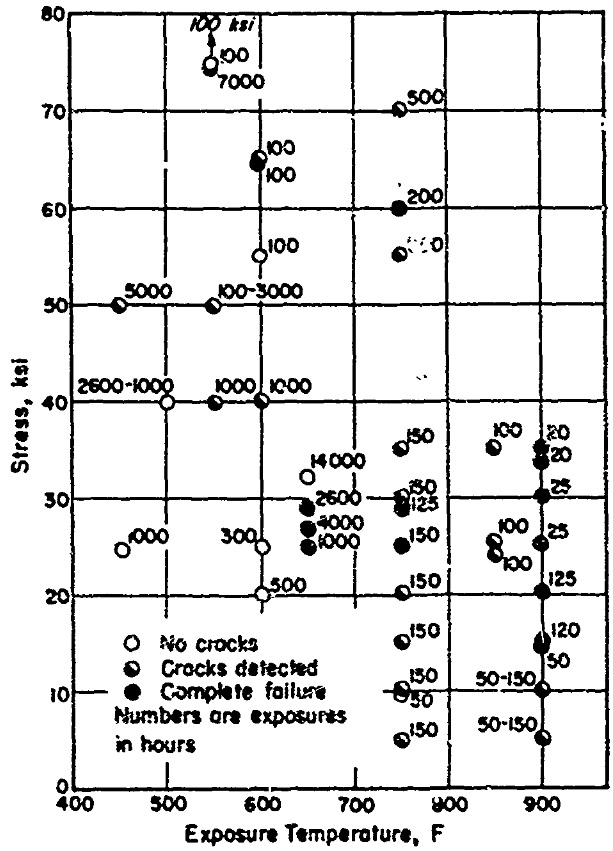


FIGURE 1-3. 6. 4. 2-1. EFFECT OF EXPOSURE VARIABLES ON THE OCCURRENCE OF VISIBLE SALT-STRESS CORROSION IN Ti-8Al-1Mo-1V ALLOY (SEVERAL ANNEALS)[11]

Long-time-exposure tests are now in progress at temperatures between 450 and 650 F that are aimed specifically at determining time and stress levels necessary for salt- ress corrosion as it might occur in advanced aircraft. Table 1-3. 6. 4. 2-1 presents the results obtained in one such test at the Boeing Company, where it is evident that property degradation occurs with increasing exposure severity. However, stress-corrosion cracking was not observed in each sample showing property degradation. This raises the question as to whether surface

TABLE 1-3.6.4.1-1. EFFECT OF THERMAL, STRESSED EXPOSURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF Ti-8Al-1Mo-1V ALLOY(8)

Rolling Temperature, F	Heat Treatment	Exposure Conditions Temp, F	Stress, ksi	Time, hr	Ultimate Tensile Strength, ksi	0.2% Offset, Yield Strength ksi	Elongation, %	Reduction in Area, %
				11/16-Inch-Diameter Bar				
1750	1400 F,24 hr, AC	No exposure (control)			136	132	18	47
		1000	15	200	147	143	16	38
1850	1650 F,1 hr, AC + 1100 F,24 hr	No exposure (control)			152	148	18	40
		1000	15	150	154	146	19	40
		1000	30	150	156	143	24	40
1950	1650 F,1 hr, AC + 1100 F,24 hr	No exposure (control)			166	150	17	26
		1000	15	150	168	148	15	21
		1000	30	150	168	146	16	18
				0.063-Inch Sheet				
1850	1700 F,1/2 hr, AC + 1400 F,2 hr	No exposure (control)			147	132	15	--
		800	65	150	147	134	6	--
		1000	25	150	155	147	19	--
				0.040-Inch Sheet (Solution Treated and Aged)				
1850	1800 F,5 min, WQ + 1000 F,8 hr	No exposure (control)			171	155	5	--
		1000	25	150	172	155	10	--
1850	1800 F,5 min, WQ + 1200 F,8 hr	No exposure (control)			164	152	7	--
		1000	25	150	172	158	6	--

TABLE 1-3.6.4.1-2. EFFECT OF THERMAL EXPOSURE WITH AND WITHOUT STRESS ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF Ti-8Al-1Mo-1V BAR FORGED AT 1850 F

Annealed at 1650 F, 1 Hr,AC + 1100 F,24 Hr,After Forging(9)

Exposure Conditions Temp, F	Stress, ksi	Time, hr	Ultimate Tensile Strength, ksi	Yield Strength (0.2% Offset), ksi	Elongation, %	Reduction in Area, %
No exposure (control)			146	140	22	28
			147	136	22	30
[illegible]	None	500	1[illegible]4	145	11	12
[illegible]	None	1000	161	--	14	18
[illegible]	40	714	156	137	13	15
[illegible]	40	1219	150	140	15	21
[illegible]	[illegible]	619	154	138	10	16

TABLE 1-3.6.4.1-3. SELECTED TEST DATA SHOWING THE EFFECTS OF THERMAL EXPOSURE WITH AND WITHOUT STRESS ON THE PROPERTIES OF Ti-8Al-1Mo-1V ALLOY[10]

Heat Treatment or Material Condition	Sheet Thickness, in	Exposure Conditions: Temp, F	Exposure Conditions: Stress, ksi	Exposure Conditions: Time, hours	Test Temp, F	Change in Tensile Properties, % of control: Ultimate Strength	Change in Tensile Properties, % of control: Yield Strength (0.2% Offset)	Change in Tensile Properties, % of control: Elongation
Mill annealed	--[a]	No exposure (control)			RT	155 ksi	145 ksi	18%
	--	650	25	15,000	RT	-5	±0	±0
	--	550	67	1,000	RT	-4.5	-4	-11%
	--	550	67	22,000	RT	-6	-5	--[a]
	--	No exposure (control)			-110	175 ksi	168 ksi	16%
	--	650	25	1,000	-110	-2	-3.5	-18
Duplex annealed	0.025	No exposure (control)			RT	157 ksi	146 ksi	17%
	0.025	550	80	1,500	RT	+3	+2.7%	-17
	0.025	No exposure (control)			550	124 ksi	99 ksi	13%
	0.025	550	80	1,500	550	±0	±0	-23
	0.050	No exposure (control)			RT	142 ksi	129 ksi	14%
	0.050	650	25	1,000	RT	+5.6	+3	±0
	--	No exposure (control)			RT	147 ksi	134 ksi	14%
	--	650	25	1,000	RT	+6.8	+8	+14
	--	No exposure (control)			400	119 ksi	100 ksi	15%
	--	650	25	1,000	400	+8.4	+4	±0
	--	No exposure (control)			650	110 ksi	87 ksi	14%
	--	650	25	1,000	650	+3.6	+2.3	-28
	--	650	25	5,000	650	+7	+5.7	+7
Duplex annealed and arc welded	0.060	No exposure (control)			RT	149 ksi	126 ksi	8%
	0.060	600	0	500	RT	+3.3	+5.5	-12
	0.060	500	0	500	RT	+0.6	-2.3	±0

TABLE 1-3.6.4.1-3. (Continued)

Heat Treatment or Material Condition	Sheet Thickness, inch	Exposure Conditions: Temp, F	Exposure Conditions: Stress, ksi	Exposure Conditions: Time, hrs	Test Temp, F	Change in Tensile Properties, % of control: Ultimate Strength	Change in Tensile Properties, % of control: Yield Strength (0.2% Offset)	Change in Tensile Properties, % of control: Elongation
Duplex annealed, fusion welded, and planished	0.050	No exposure (control)			RT	151 ksi	--	--
	0.050	400	25	5,000	RT	-3.3	--	--
	--	650	25	1,000	RT	+6	--	--
	--	650	25	5,000	RT	+2	--	--
	0.050	No exposure (control)			400	124 ksi	--	--
	0.050	400	25	5,000	400	-2.[illegible]	--	--
	--	650	25	1,000	400	+[illegible]	--	--
	--	650	25	5,000	400	+5	--	--
	0.050	No exposure (control)			650	11[illegible] ksi	--	--
	0.050	400	25	5,000	650	-4.4	--	--
	-	650	25	1,000	650	+10.7	--	--
	--	650	25	5,000	650	+2.6	--	--

(a) Dash indicates data not reported

TABLE 1-3.6.4.1-4. EFFECT OF CYCLIC AND STEADY-STATE EXPOSURE ON ROOM-TEMPERATURE TENSILE PROPERTIES OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY[5]

	Exposure Conditions					Test	Change in Tensile Properties, % of control		
Time, hrs	Temperature State	Temperature F	Stress State	Stress, ksi		Temp, F	Ultimate Strength	Yield Strength	Elongation
	No exposure (controls)					RT	140 ksi	128 ksi	16%
						500	111 ksi	89 ksi	15%
2000	Steady	500	Steady	0		RT	+2.5	+3	-3
5000	Steady	500	Steady	0		500	+1	-1	-4
2000	Steady	500	Steady	40		RT	+3	+2	-4
2000	Cyclic[a]	500	Cyclic[b]	40		RT	+3	+.5	-17
2000	Steady	500	Steady	40		500	+3	-1	-13
2000	Cyclic[a]	500	Cyclic[b]	40		500	+4	-2	-18
2000	Steady	650	Steady	40		RT	+5	+2.5	-4
5000	Steady	650	Steady	40		RT	+6.5	+3	-19

(a) Temperature changed from room temperature to 500 F in ~10 minutes, held at temperature about 2.5 hours and cooled to room temperature in ~10 minutes. Cycle then repeated.

(b) Stress applied for about 2.5 hours out of every ~3 hour cycle. Relaxation to zero-stress conditions about every 3 hours.

TABLE 1-3.6.4.2-1. EFFECT OF ELEVATED TEMPERATURE EXPOSURE IN THE PRESENCE OF SALT ON THE PROPERTIES OF DUPLEX ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET(5)

Exposure Conditions						Change in Tensile Properties, % of control	
Salt Application	Temp, State	Temp, F	Stress, State	Stress, ksi	Time, hours	Ultimate Strength	Elongation
None	No exposure (control)					134 ksi	14%
Dry pack[a]	Steady	450	Steady	40	2000	+6	+7
Ditto	"	450	"	40	5000	+8	±0
"	"	500	"	40	1000	+8 to 14	-7 to 50
"	"	500	"	40	2000	+4.4 to 15	Up to -70
"	"	500	"	40	5000	+3	-85
"	"	550	"	40	1000	-2 to -22	-28 to -90
"	"	600	"	40	1000	-51 to -59	Failed
None	No exposure (control)					141 ksi	16%
Wet solution[b]	Cyclic[c]	550	Steady	42	~2000	+2.8	-18.8
Ditto	"	550	"	63	~2000	+4.2	-25
"	"	550	"	77	~2000	+5.6	-31 to -38

(a) NaCl slurry dried on specimen.
(b) Aqueous solution 3.5% NaCl.
(c) Two and one-half hours at temperature followed by air cooling to ambient temperature, dipped in salt solution, and raised again to elevated temperature in about 20 minutes.

effects are difficult to detect or whether metallurgical instability is involved. Insufficient data are presently available to form conclusions However, an investigation at the Lockheed-California Company has shown that in salt-exposed specimens, surface damage may often be detected using dye-penetrant, black-light technique prior to degradation of tensile properties. Conversely, property degradation may occur without surface-damage detection.

In summarizing, the fact that salt-stress-corrosion failures are known to be rare in applications such as engines (where conditions appear to be relatively severe), is emphasized. Study in all other exposure conditions is too limited to permit the drawing of conclusions except that salt-stress-corrosion reactions have been observed in laboratory tests on Ti-8Al-1Mo-1V alloy over a wide range of conditions.

1-3.7 REFERENCES

(1) Austin, D. E., "Metallographic Study of Ti-8Al-1Mo-1V", Boeing document T6-3114 (August 31, 1964; updated April 26, 1965).

(2) Blackburn, M. J., "Phase Transformations in the Alloy Ti-8Al-1Mo-1V", The Boeing Company, paper presented at the Fall Program of of the Metallurgical Society of AIME (1964).

(3) "Properties of Ti-8Al-1Mo-1V, The High Strength Titanium Alloy for Superior Resistance to Creep", TMCA Data Memorandum.

(4) Day, D. L., and Kessler, H. D., "Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr", Summary Report on Contract NOas 59-6227-c (December, 1961).

(5) Unpublished data from The Boeing Company.

(6) Seagle, S. R., "Effect of Cooling Rate From the Annealing Temperature on the Tensile Properties of Ti-8Al-1Mo-1V Sheet", Reactive Metals Memorandum (February 19, 1964).

(7) "Ti-8Al-1Mo-1V Sheet and Plate - Conditions of Heat Treatment Available and Their Influence", TMCA Data Memorandum, EFE (January, 1963).

(8) Preliminary information reported by Titanium Metals Corporation of America under Contract NOas-59-6227-C.

(9) Soltis, P. J., "Evaluation of TMCA Ti-8Al-1Mo-1V Alloy", Report No. NAMC-AML-1207, Naval Air Material Center, Aeronautical Material Center, Aeronautical Materials Laboratory (March 24, 1961).

(10) Compilation of data from:

(a) "Investigation of Long Term Exposure Effects Under Stress on SST Structural Materials", Report NA-64-758, North American Aviation, Incorporated (July, 1964).

(b) Freeman and Raring, "Progress Report of the NASA Special Committe on Materials Research for SST", NASA TN D-1798 (May, 1963).

(c) "Intermittent Creep and Stability Studies on SST Materials", Report AFML-TDR-64-138, GD/Ft. Worth (March, 1964).

(d) Preliminary information reported by Lockheed Airplane Company under Contract AF 33(657)-11460.

(e) "Fracture Toughness and Tear Tests", The Boeing Company, AF 33(657)-11461, Project 648 D (June, 1964).

(f) "Thermal Stability of Arc-Welds in Ti-8Al-1Mo-1V Alloy", TMCA Data Sheet (April, 1964).

(11) Boyd, W. K., and Fink, F. W., "The Phenomenon of Hot-Salt Stress Corrosion Cracking of Titanium Alloys", NASA Contractor Report NASA Cr-117 (October, 1964).

1-4 Titanium Alloy Ti-6Al-4V

1-4.0 GENERAL REMARKS

Several grades of Ti-6Al-4V alloy are made, one of which is a high-purity grade, ELI, designed for cryogenic usage. The standard grade contains an intermediate amount of interstitial element and is the grade used for airframe application. The Ti-6Al-4V alloy has been the most widely used of all titanium grades and is readily available in most mill product forms.

1-4.1 COMMERCIAL DESIGNATION

Designations	Producer	Forms Available[a]
C-120AV	Crucible Steel Co.	B,b,P,W
HA-6510	Harvey Aluminum Co.	B,b,E,W
OMC-165-A	Oregon Metallurgical Corp.	B, castings
RMI-6Al-4V	Reactive Metals, Inc.	B,b,P,S
Ti-6Al-4V	Titanium Metals Corp.	B,b,P,S,W,E
MET-RMD-1	Misco Division, Howmet Corp.	Castings

(a) B = billet, b = bar, P = plate, S = sheet, s = strip, W = wire, E = extrusions.

1-4.2 ALTERNATE DESIGNATIONS (COMMON NAMES

6-4, IMI-318A (British)

1-4.3 ALLOY TYPE

Alpha-beta (lean beta content)

1-4.4 COMPOSITION, RANGE OR MAXIMUMS, %

Major Elements

	Standard Grade	ELI Grade
Al	5.5-6.75	5.5-6.5
V	3.5-4.50	3.5-4.5
Fe	0.30	0.15

Interstitial Elements

	Standard Grade	ELI Grade
O	0.20	0.13
C	0.10	0.08
N	0.05	0.05
H	0.015 sheet 0.0125 bar	0.015 sheet

1-4.5 SPECIFICATIONS

AMS-4911	MIL-T-9046F, Type III, Comp. C
AMS-4935	MIL-T-9047-C15
AMS-4928	T-12117(ORD)C1120
OS-10737	
OS-10740	

1-4.6 DESCRIPTION AND METALLURGY

1-4.6.1 Composition and Structure[1]

The Ti-6Al-4V alloy is an alpha-beta alloy in which an alpha stabilizer, aluminum, and a beta stabilizer, vanadium, are combined. The 6 percent aluminum addition raises the strength of the alpha phase by a solid-solution strengthening mechanism, while the beta phase may be strengthened by precipitation hardening (of alpha) during an aging treatment. The relatively high-alpha-stabilizer content is both beneficial and disadvantageous: beneficial since it imparts strength over the entire service temperature range and disadvantageous from the standpoint of room-temperature formability. However, some room-temperature forming is possible (normally 3 to 5T bends are made without difficulty) and more complex forming is possible by using warm forming techniques.

The response of the Ti-6Al-4V alloy to heat treatment and the types of microstructures resulting from these heat treatments can be discussed in terms of the phase relationships. A schematic vertical section of the ternary diagram is shown in Figure 1-4.6.1-1.

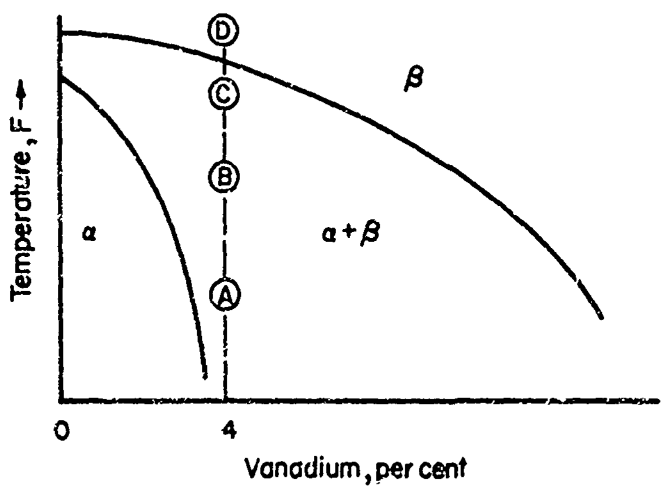


FIGURE 1-4.6.1-1. SCHEMATIC DIAGRAM SHOWING THE PHASE RELATIONSHIPS FOR THE Ti-6Al-4V ALLOY[1]

Annealing temperatures, indicated by Point A, usually are in the range from 1200 to 1400 F. The resulting structure is mainly alpha phase, with

beta retained in the grain boundaries. This high proportion of alpha is a result of the relatively high solubility of vanadium in alpha and the presence of aluminum, an alpha stabilizer. By solution annealing and quenching from temperatures higher in the alpha-beta field (Points B to C), the alloy can be strengthened by subsequent aging. This increase in heat-treatment response is caused both by the increased amount of beta phase in the structure and the change in alloy content of the beta phase with increasing temperature. As the solution-annealing temperature is increased, the vanadium content of the equilibrium beta phase eventually is lowered below the limit at which beta phase is retained on quenching; the beta transforms partially to alpha prime (martensite) after solution annealing at about 1750 F, whereas at 1550 F, beta is retained. At the latter solution-annealing temperature, however, the beta phase is mechanically unstable after quenching, and martensite can then be formed during plastic straining. This condition is characterized by a low ratio of yield to ultimate tensile strengths. Maximum heat-treatment response is attainable after solution annealing in the beta field (D); however, the strength increase is offset by a considerable loss of ductility ensuing from the transformed structure, so that solution anneals usually are not carried out in the all-beta range but rather from intermediate to high in the alpha-beta range (Points B to C).

The general effects of carbon, oxygen, and nitrogen on the Ti-6Al-4V alloy can be summarized as follows:

(1) The beta-transus temperature is increased with increased amounts of the interstitials.

(2) An increase in strength occurs with increased interstitial content. At low temperatures, <-320 F, particularly when severe stress systems are involved, brittleness in high-interstitial-content alloys may occur. At intermediate temperatures, up to 500 F, an improvement in strength without an adverse loss of ductility is found. The strengthening effect of the interstitials decreases with increasing temperatures.

(3) The transformation kinetics of the beta-to-alpha reaction are accelerated by the presence of these interstitials dissolved in the beta phase. However, for materials containing normal interstitial levels solution annealed in the alpha-beta field, most of the interstitial content is preferentially dissolved in the alpha phase, so that little or no effect on the transformation kinetics is observed.

(4) Notch sensitivity is increased with increasing interstitial content. The notch tensile properties of the Ti-6Al-4V alloy at different levels of interstitial content have been investigated. It was found that the notch sensitivity is increased by increased interstitial content, with the effects becoming more pronounced at low testing temperatures.

The adverse effects of hydrogen in titanium alloys have been the subject of numerous investigations. It appears that, in comparison with other alpha-beta alloys, the Ti-6Al-4V alloy is relatively insensitive to hydrogen embrittlement so long as the hydrogen content is kept within specifications.

Like other alpha-beta titanium alloys, the Ti-6Al-4V alloy exhibits sensitivity to slow-strain embrittlement when the hydrogen content is excessive. It has been postulated that this is a form of strain aging, in which the precipitation of titanium hydride at an interface under strain is the embrittling mechanism. Room-temperature stress-rupture tests on notched and unnotched specimens have been used to evaluate the embrittling effects of hydrogen. With one exception, the hydrogen tolerance in all the conditions tested was greater than 200 ppm, as established by the unnotched stress-rupture test; the one exception was heat treated to produce a very coarse alpha grain size and had a continuous beta matrix; it is not representative of material encountered in commercial usage.

The interstitial elements, carbon, oxygen, and nitrogen, are known to increase the beta-transus temperature. The alpha-beta to beta transus is about 1820 F for the Ti-6Al-4V alloy. For the annealed condition, strengths are increased without an appreciable loss of ductility when moderate amounts of interstitials are present. In the optimum heat-treated conditions, tensile strengths are increased, while still retaining acceptable ductilities.

1-4.6.2 Deformation Practice and Effects

Forging breakdown of Ti-6Al-4V ingots is done at temperatures ranging from high in the alpha-beta field to slightly above the beta-transus temperature. Subsequent forging is generally done at the lowest temperature, below the beta transus, where the alloy possesses the required fabricability. Such practice minimizes oxidation and air contamination and produces an alpha-beta structure having good ductility. The following forging temperatures have been recommended:

Breakdown Temperature, F	Finish Temperature, F
1750-1850	1650-1750

Primary working of Ti-6Al-4V at temperatures entirely in the beta field has been considered undesirable because of the reduced ductility of the resulting acicular or Widmanstatten alpha-beta

structure. Recent evidence, however, suggests that beta processing can produce increased fracture toughness, after heat treatment, while affording improved fabricability due to the higher processing temperature.[2] Where secondary formability in the finished product is not a major consideration, the benefits of increased fracture toughness may greatly offset the loss of tensile ductility in such beta-processed material. Accordingly, beta processing will most probably be restricted to mill products of moderately heavy section size, e.g., to extrusions, forgings, and plate, as opposed to thin-gage sheet. Properties of pancake forgings produced by conventional forging and beta forging are compared in Table 1-4.6.2-1.[2]

Beta-worked forgings also exhibited equivalent notched-fatigue properties compared with alpha-beta processed material. These data are shown in Figure 1-4.6.2-1.[2]

Elevated-temperature forming operations are used to form thin-section products from Ti-6Al-4V. A 400 to 600 F temperature range is used for forming in the hydropress operation, while higher temperatures 900 to 1600 F are used in a variety of operations from hydroforming to spinning. Room-temperature forming is used extensively too in operations that do not require severe deformation. The advantages of elevated temperatures for forming are illustrated by the following bend-test data.

Test Temperature, F	Minimum Bend Radius, radius-to-thickness ratio
RT	4.5 to 5.0
400	~ 3.5
600	3.0 to 3.5
800	~ 3.0
1000	2.5 to 3.0
1200	2.0 to 2.5
1400	~ 2.0
1600	~ 2.0

TABLE 1-4.6.2-1. PROPERTIES OF CONVENTIONALLY AND BETA-PROCESSED Ti-6Al-4V FORGINGS[2][a]

Forging Condition	Heat Treatment After Forging	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, %	Reduction in Area, %	K_{Ic},[b] ksi $\sqrt{in.}$
Alpha + beta	1725 F 1 hr; WQ + 1000 F 4 hr; AC	167	154	13	48	45
Alpha + beta	1300 F 2 hr; AC	145	135	15	41	56
Beta	1725 F 1 hr; WQ + 1000 F 4 hr; AC	168	148	10	29	70
Beta	1300 F 2 hr; AC	142	129	13	35	91

(a) Properties were determined on longitudinal specimens.
(b) K_{Ic} values determined on fatigue-cracked single-edge-notched specimens using four point loading.

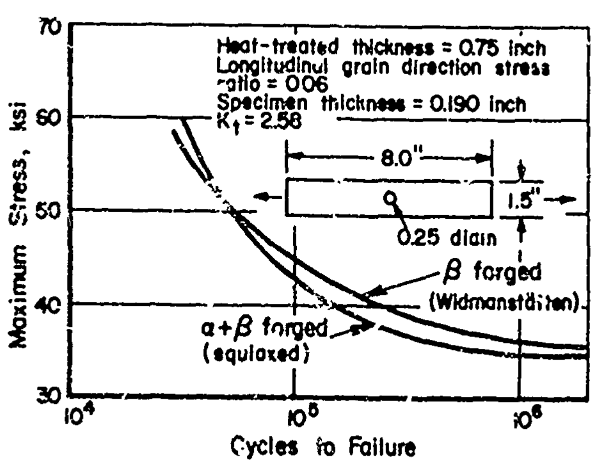


FIGURE 1-4.6.2-1. NOTCHED FATIGUE PROPERTIES OF Ti-6Al-4V FORGINGS, CONVENTIONALLY AND BETA PROCESSED[2]

Moderate elevated temperatures also increase uniform elongation, although sufficient uniform elongation exists at room temperature to permit many forming operations. Forming is approximately equivalent for Ti-6Al-4V alloy in either the annealed or solution-heat-treated conditions.

The introduction of plastic strain at temperatures below the recrystallization temperature produces residual stress. For example, the bending and stretch forming of sheet-metal parts, or strains caused by the assembly of parts, may result in high internal stresses without external loading. Further, the Bauschinger effect, a decrease in yield strength in a direction opposite to plastic straining, may adversely affect the performance of the final part.[1]

Data concerning the Bauschinger effect and the results of stress-relief anneals on the Ti-6Al-4V alloy have been summarized from work done at Convair:

(1) As-received material strained in tension to a 1 percent permanent set exhibited a 40 percent loss in compressive yield strength.

(2) Heat-treated material (solution annealed 2 hours at 1500 and 1650 F, quenched, and aged 6 hours at 500 F), and strained in tension to a 1 percent permanent set, exhibited a 45 percent loss in compressive yield strength.

(3) After straining in tension to a 1 percent permanent set, solution treatment and aging (not specified) completely restored the compressive yield strength.

(4) For material solution annealed at 1500 and 1650 F, quenched, strained in tension to 1 percent permanent set, and aged 6 hours at 500 F, the compressive yield strength was 93 percent that of the unstrained material.

(5) Solution treatment at 1550 and 1650 F, followed by straining in tension to a 1 percent permanent set, and aging for 6 hours at 1000 F, gave complete recovery of compressive yield strength for the material solution treated at 1550 and 94 percent recovery for the material solution treated at 1650 F.

(6) Solution treatment and aging (not specified), following extension to a 3 percent permanent set gave 98 percent recovery of compressive yield strength.

Thus, a complete solution-annealing and aging treatment may be expected to restore nearly all the compressive yield strength after straining. If the material is strained after solution treatment and then aged, a large proportion of the compressive yield strength is restored.

1-4.6.3 Heat Treatment Practice and Effects

1-4.6.3.0 General Remarks

Heat treatment of the Ti-6Al-4V alloy is used to impart the desired combinations of strength, ductility, and thermal stability to the final product. The following sections summarize the available data for stress-relief, annealing, and solution-plus-aging heat treatments.

1-4.6.3.1 Stress-Relief Annealing

Stress-relief annealing treatments are intended to relieve the residual stresses and to restore yield strength without otherwise affecting mechanical properties. Anneals for periods of 1/2 to 1 hour in the temperature range of 1000-1200 F are commonly used for this purpose. In some applications, the stress-relief anneal can be done in fixtures to remove springback or warpage introduced by the forming operation. Data showing the experimental relaxation of residual stress are given in Figure 1-4.6.3.1-1[4].

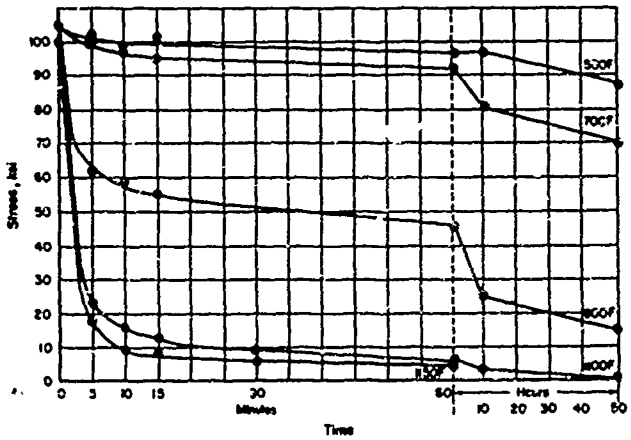


FIGURE 1-4.6.3.1-1. RELIEF OF RESIDUAL STRESS VERSUS TIME AT 500 F, 700 F, 900 F, 1100 F, AND 1150 F FOR Ti-6Al-4V ALLOY[4]

Section size, prior history, and the degree of stress relief desired determine the magnitude of the required stress-relief anneal. To minimize oxidation, it is preferable to hold the time and temperature as low as possible.

1-4.6.3.2 Annealing

Annealing heat treatments for the Ti-6Al-4V alloy usually are for 1 to 2 hours at 1300 to 1500 F, followed by furnace cooling to about 1100 F, then air cooling to room temperature. Variations in time of exposure, temperature range, and cooling rates are used, depending on user experience and part size. The section size may be of importance as it affects the cooling rate. For example, slow

cooling of larger sections is helpful in preventing warpage and the introduction of residual stress from inhomogeneous cooling. Regardless of the variation in technique, the annealing treatment is designed to achieve a mixed alpha-beta structure that is ductile and stable. Most of the Ti-6Al-4V alloy supplied by the producers is supplied in the annealed condition.

Duplex annealing of Ti-6Al-4V has also been investigated and found to produce slightly better fracture toughness and resistance to crack growth in salt water than conventional mill annealing. The duplex method consists of annealing first at a temperature high in the alpha-beta field, such as 1750 F, then air cooling to room temperature, followed by reannealing at a stabilization temperature, such as 1250 F, and air cooling. Ten minutes of exposure to the high temperature and 4 hours' exposure to the lower temperature produce the above-mentioned improvements in toughness and crack growth rates in salt water at about the same strength level achieved by mill annealing. (2)

1-4.6.3.3 Strengthening Heat Treatments

High strengths are attainable in the Ti-6Al-4V alloy through a solution-annealing and aging heat-treatment process. A considerable amount of data have been accumulated showing effects of different cycles of solution annealing and aging on mechanical properties. There is general agreement that desirable properties are obtained by solution annealing in the temperature range of 1550 to 1750 F, quenching, and aging at temperatures from 900 to 1100 F. (1)

1-4.6.3.3.1 Hardenability

The hardenability of the heat-treatable titanium alloys is measured by their ability to be cooled from the solution-annealing temperature without transformation of the beta phase to omega or alpha. The standard Jominy end-quench test frequently is used to measure hardenability.

In compariaion with many alloy steels, titanium alloys are relatively shallow hardening. This, in part, is a result of their low thermal conductivity. It should be noted that steels are quenched to a relatively hard martensite condition, whereas titanium alloys are quenched to a relatively soft condition. Figure 1-4.6.3.3.1-1 shows a series of end-quench hardenability curves for Ti-6Al-4V alloy with various interstitial contents; all these were solution treated 100 F above the beta transus. The high hardness near the quenched end indicates shallow hardenability, i.e., hardness has been increased through beta decomposition during cooling. Figure 1-4.6.3.3.1-2 represents the effects of section size on the Ti-6Al-4V alloy quenched from 1550 F, and also includes the hardness after aging 24 hours at 900 F. It can be seen that even at distances as great as 3 to 4 inches from the quenched end, there still is an appreciable aging response; however, the strength near the centers of large sections is appreciably lower than that obtained in small sections. This is further demonstrated by the data of Figure 1-4.6.3.3.1-3. In practice, full strength in Ti-6Al-4V sections over about 1 inch in thickness is not expected. Other titanium alloys can be hardened in thicker sections, as shown previously in Table 1-0.0-1.

1-4.6.3.3.2 Solution Annealing

The solution-annealing treatment selected for a given application is based on the desired mechanical properties and section size of the material. In general, for both aged and unaged material, the tensile strength is increased by an increased solution temperature. Figures 1-4.6.3.3.2-1 and 1-4.6.3.3.2-2 show typical tensile properties in the solution-treated and in the solution-treated and aged conditions, respectively, for a number of solution temperatures and aging cycles. Maximum ductility in the solution-treated condition is obtained at about 1550 F; this may be of considerable importance in sheet applications in which forming operations are necessary. The minimum in the ratio of yield-to-ultimate tensile strengths is low (approximately 0.70), also indicative of good formability. Where maximum strength is required, solution treatment at a higher temperature is used: 1700 to 1750 F usually is recommended.

The solution temperature is effectively lowered when the piece is not immediately quenched. The effects of various time delays before water quenching on tensile properties are shown in Figure 1-4.6.3.3.2-3 for two solution temperatures.

1-4.6.3.3.3 Aging Heat Treatments

The aging of Ti-6Al-4V alloy may be accomplished in exposures of from 1 to 24 hours in the temperature range of 900 to 1100 F. Overaging occurs at temperatures above this range, at a considerable sacrifice in strength and only a slight improvement in ductility. Figure 1-4.6.3.3.3-1 shows the effect of aging time at 900 F on the tensile properties of specimens solution treated at 1550 F. It is seen that the properties remain essentially unchanged after an aging time of about 8 hours. Aging treatments increase the strength of Ti-6Al-4V metal through the formation of transformation products, primarily alpha from beta.

Properties of aged Ti-6Al-4V forgings, processed in the beta field, were compared with the properties of aged alpha-beta processed material in Table 1-4.6.2-1. As shown in that table, a 55 percent increase in fracture toughness was achieved

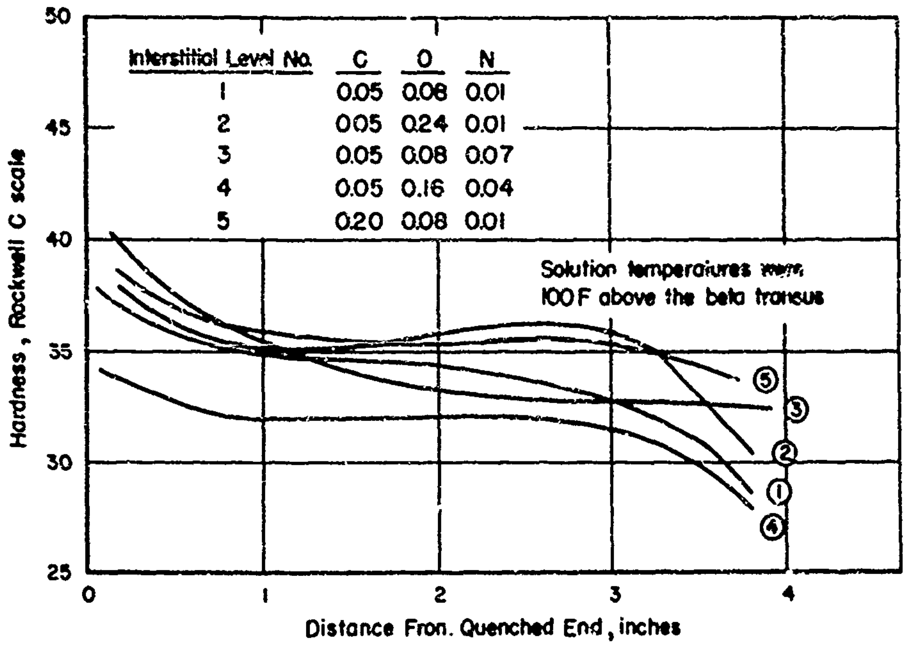


FIGURE 1-4.6.3.3.1-1. END-QUENCH HARDENABILITY CURVES FOR Ti-6Al-4V ALLOY(1)

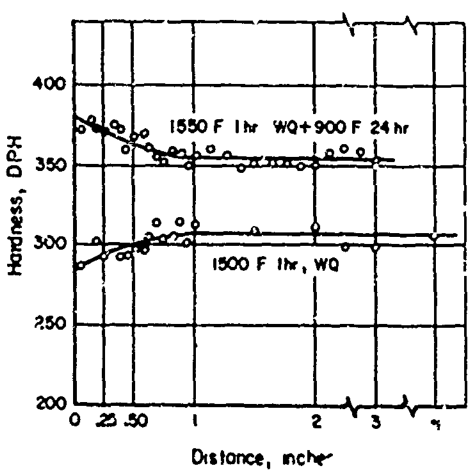


FIGURE 1-4.6.3.3.1-2. THE EFFECT OF AGING ON HARDNESS OF A Ti-6Al-4V SPECIMEN END QUENCHED FROM 1550 F(1)

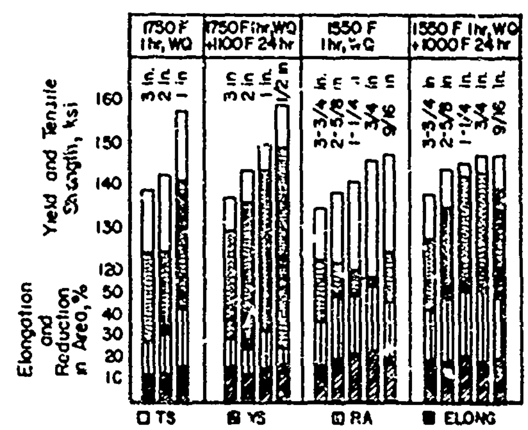


FIGURE 1-4.6.3.3.1-3. THE EFFECT OF SECTION SIZE ON TENSILE PROPERTIES OF Ti-6Al-4V(1)

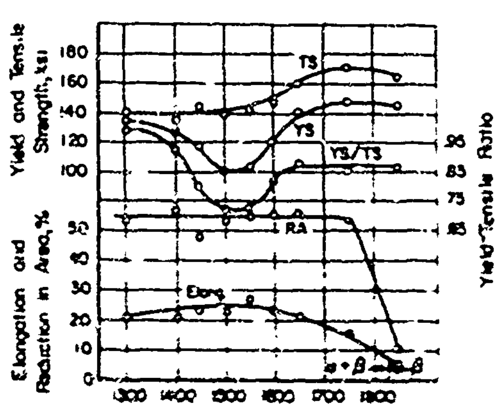


FIGURE 1-4.6.3.3.2- THE EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF Ti-6Al-4V(1)

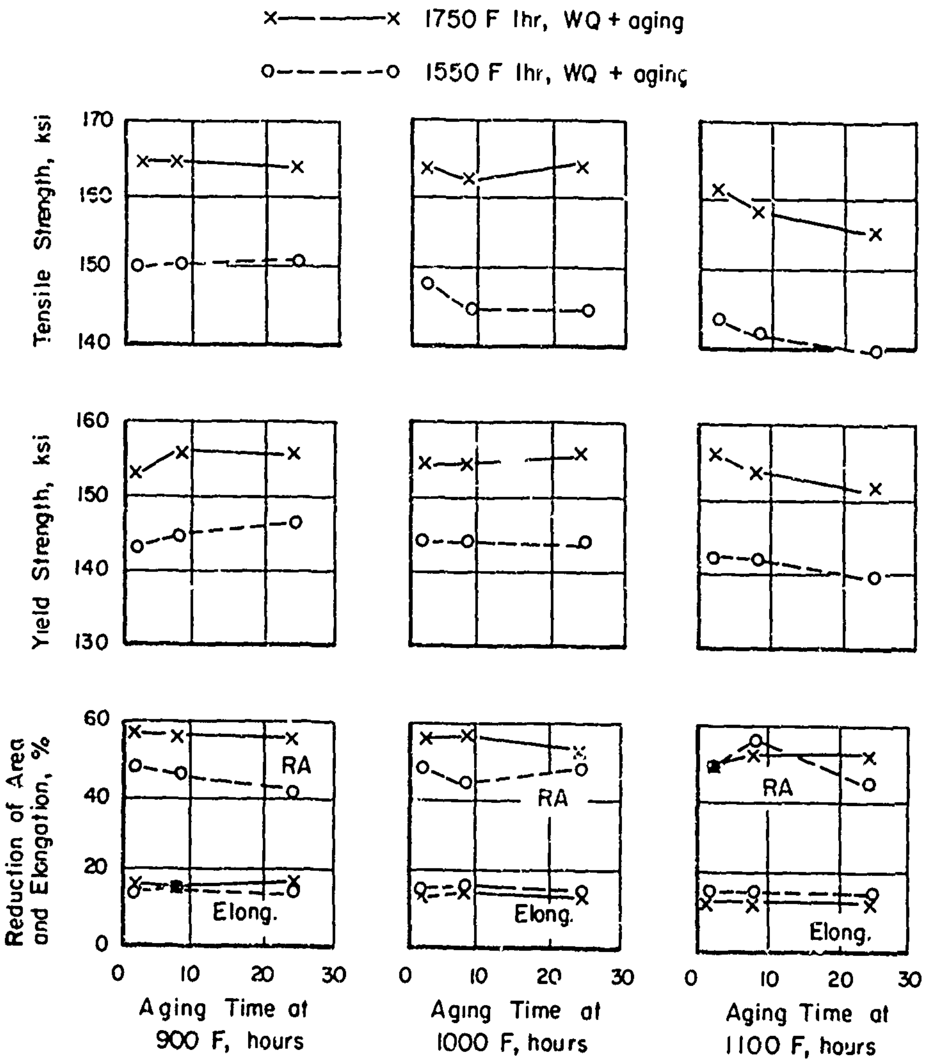


FIGURE 1-4.6.3.3.2-2. THE COMBINED EFFECT OF SOLUTION TEMPERATURE (1 HOUR), AGING TEMPERATURE, AND AGING TIME ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF Ti-6Al-4V 5/8-INCH-DIAMETER BAR(1)

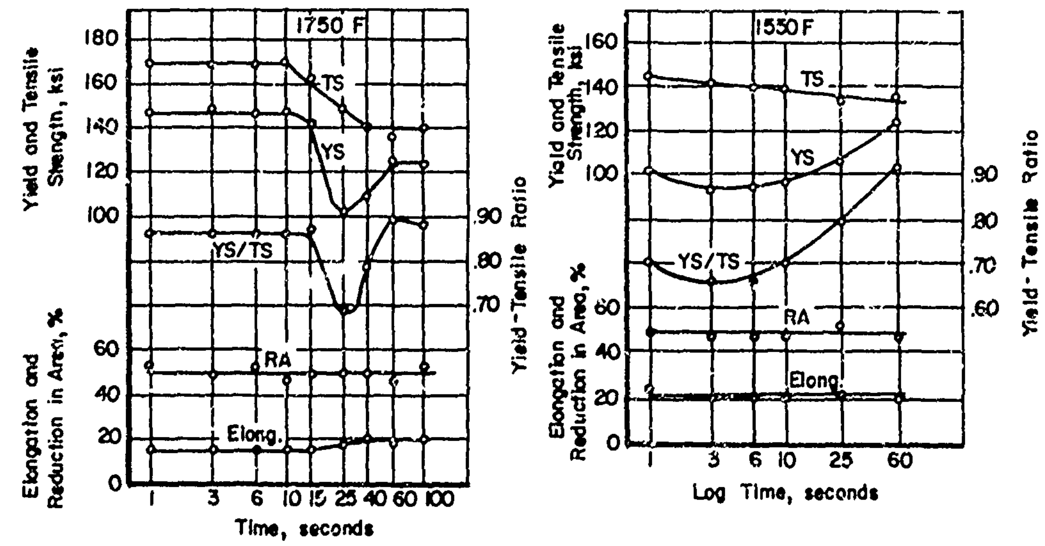


FIGURE 1-4.6.3.3.2-3. THE EFFECT OF DELAYED WATER QUENCHING FROM 1750 AND 1550 F ON THE TENSILE PROPERTIES OF Ti-6Al-4V ALLOY(1)

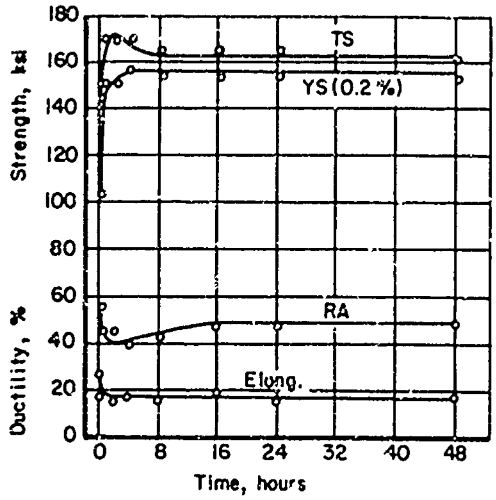


FIGURE 1-4. 6. 3. 3. -1. THE EFFECT OF AGING TIME 9 F ON THE TENSILE PROPERTIES SPECIMENS SOLUTION TREATED AT 1550 F[1]

in aged, beta-forged material over that produced in conventionally processed material by the same STA treatment.

Overaging of Ti-6Al-4V further increased fracture toughness at the expense of strength for both beta-processed and conventionally processed plate. Data showing these effects of overaging are given in Table 1-4. 6. 3. 3. 3-1. [2]

1-4. 6. 4 Stability

The Ti-6Al-4V alloy has the ability to retain the original mechanical properties after prolonged exposure at elevated temperature in a variety of environments. Certain environments can cause either embrittlement or softening -- embrittlement by hot-salt stress corrosion, softening by high elevated-temperature exposure for example -- but in general, under ordinary service conditions, the Ti-6Al-4V alloy is considered stable. Changes in properties are usually well within the acceptable limits of stable behavior.

1-4. 6. 4. 1 Thermal Stability

The thermal stability of Ti-6Al-4V alloy of course depends largely upon its heat-treated condition. Elevated-temperature exposure of solution-heat-treated material will result in an aging reaction, the extent of which depends on exposure conditions, and may lead to an increase in strength and decrease in ductility. While it would appear to be unnecessary to refer to elevated-temperature service exposure of solution-treated metal, it should be kept in mind that some forming operations are performed in the solution-heat-treatment temperature range. In these cases, the material should either be aged or annealed prior to service in order to stabilize the structure. One effect of long-time service exposure on solution-treated material (effectively long time aging) is shown below. [5]

930 F Exposure Time, hours (unstressed)	Room-Temperature Tensile Properties of 1560 F Treated Bar[5] UTS, ksi	0. 2% Offset YS, ksi	Elongation, %
50	144	140	12
500	135	134	13

The stressed thermal stability of annealed Ti-6Al-4V alloy is indicated on the next page as well as in Figure 1-4. 6. 4. 1-1. [1]

TABLE 1-4. 6. 3. 3. 3-1. EFFECTS OF OVERAGING ON STRENGTH AND FRACTURE TOUGHNESS OF Ti-6Al-4V[2]

Type of Processing	Heat Treatment	Ultimate Tensile Strength, ksi	K_{Ic}, ksi $\sqrt{in.}$
Conventional, alpha-beta processing	1725 F, WQ + Aged 1000 F, 4 hr, AC	173	49
Conventional, alpha-beta processing	1725 F, WQ + Overaged 1250 F, 4 hr, AC	157	60
Beta processed	1725 F, WQ + Aged 1000 F, 4 hr, AC	168	83
Beta processed	1725 F, WQ + Overaged 1250 F, 4 hr, AC	153	92

100-Hour, 750 F, Stressed Thermal Exposure at 1290 F (15 Hours) of Annealed Ti-6Al-4V Bar[5]

Condition	Exposure Stress, ksi	UTS, ksi	0.2% Offset YS, ksi	Elongation, %
Annealed	None	123	117	14
Exposed	50	1[illegible]3	124	14
Exposed	70	133	122	11

It should be pointed out that the material in both cases was air cooled from the annealing temperature rather than slow cooled to about 1000 F. The recommended slow cooling treatment results in further stabilization of the mixed alpha-beta structure. Selected thermal stability data of mill annealed Ti-6Al-4V alloy sheet (slow cooled from annealing temperature) are given in Table 1-4.6.4.1-1.[6]

The stressed thermal stability of solution treated and aged Ti-6Al-4V alloy is shown in Figure 1-4.6.4.1-2[1] and in Tables 1-4.6.4.1-2[7] and 1-4.6.4.1-3[6]. While many extremely long-time exposure data have not been generated, the exposure data from intermediate-length tests do not indicate significant degradation of properties. Exposure times up to 14,000 to 15,000 hours have shown no significant effect on static tensile or on notch strengths.

The Ti-6Al-4V alloy, in the beta-processed plus solution-treated and aged as well as overaged conditions, has exhibited good thermal stability during 450 F, and 550 F exposures under a sustained stress of 25 ksi. As shown in Figure 1-4.6.4.1-3[2], only minor variations were produced in ultimate tensile strength and fracture toughness (as revealed by stress-intensity factors) during exposure times to 2500 or 5000 hours.

1-4.6.4.2 Chemical Stability

The chemical activity of Ti-6Al-4V alloy increases with increasing temperature. The most readily observed reaction illustrating the temperature effect is oxidation. Ti-6Al-4V alloy, like almost all titanium alloys, shows a surface discoloration on elevated-temperatures air exposures. Ti-6Al-4V shows discoloration as low as at 550 F after very long times. Various degrees of surface discoloration are observed, and increasing titanium-oxygen reactivity is indicated in exposures of increasing severity by stronger color. In 1000 F exposure, scale build up can occur in 100 hours. Appreciable scale forms in 10 hours at 1100 F and in as little as 1 hour at 1200 F. While tensile properties appear to be relatively unaffected by these light scales formed at low- to moderately high-temperature exposure, fatigue properties can be slightly degraded. At these temperatures and higher temperatures, bend properties are affected as shown in Table 1-4.6.4.2-1.[1]

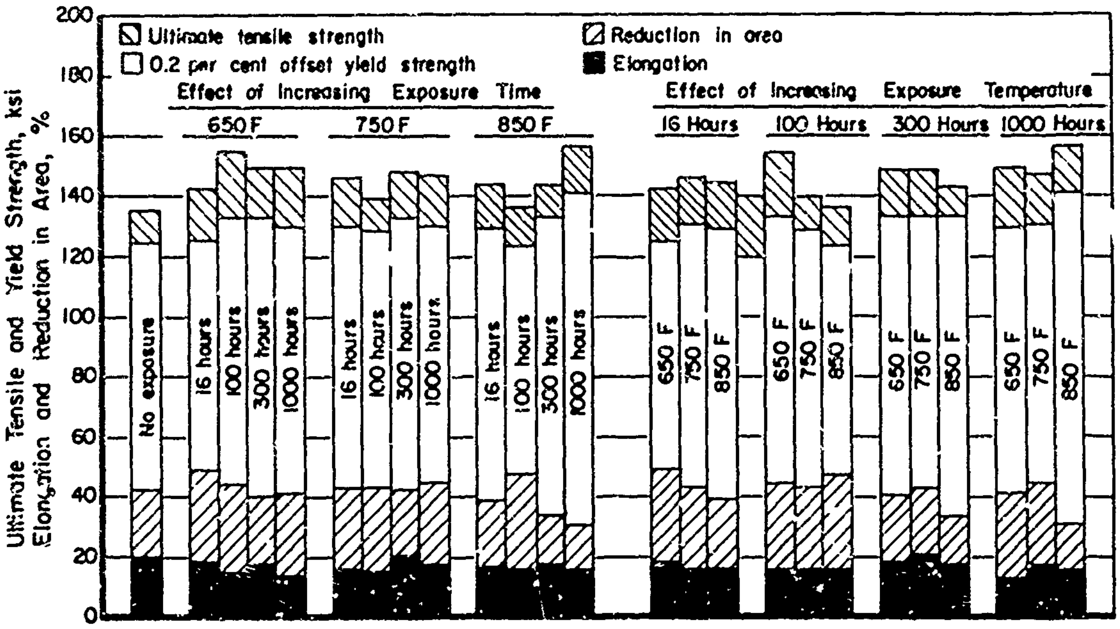


FIGURE 1-4.6.4.1-1. THERMAL STABILITY OF ANNEALED Ti-6Al-4V AS AFFECTED BY EXPOSURE TIME AND TEMPERATURE[1]

1300 F, 2 hours, air cooled.
Exposure stress: 50 ksi.

TABLE 1-4.6.4.[illegible] EFFECT OF ST[illegible]ED A[illegible] [illegible]D THERMAL EXPOSURE ON ANNEALED Ti-6Al-4V SHEET PROP[illegible]

Sheet Thickness, inch	Exposure Conditions: Temperature, F	Stress, ksi	Time, hours	Test Temperature, F	Tensile Properties: Ultimate Strength, ksi	Yield Strength (0.2% Offset), ksi	Elongation, %
0.040	No exposure (control)			-110	170	160	14
	550	None	7000	-110	170	161	14
	No exposure (control)			RT	145	137	13
	550	None	7000	RT	143	135	14
0.025	No exposure (control)			RT	136	128	12
	550	72	5000	RT	144	132	13
	No exposure (control)			550	105	89	10
	550	72	5000	550	107	88	10

TABLE 1-4.6.4.1-2. THERMAL STABILITY OF SOLUTION HEAT TREATED AND AGED Ti-6Al-4V ALLOY[7]

Heat treatment: 1700 F, 20 minutes, water quench, plus 1000 F, 4 hours, air cool

Exposure Temp, F	Exposure: Stress, ksi	Creep, %	Average Properties: 0.2% Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation in 2 Inches[a], per cent	Reduction in Area, %
				100 Hours		
	(Base)		177	186	8	39
500	100	0.14	171	179	7	31
600	95	0.06	172	178	6	29
700	70	0.11	171	182	6	32
800	45	0.24	171	181	4	29
900	20	0.25	175	183	7	30
				1000 Hours		
			177	186	8	39
500	100	0.06	174	184	6	29
600	95	0.19	178	187	6	27
700	70	0.34	172	187	5	25
800	40	0.54	176	187	5	30
900	15	0.96	170	177	4[b]	26
900	--	--	176	189	6	34

(a) Includes fracture within 2-inch gage length only.
(b) All fractures occurred outside 2-inch gage length. True value would be higher.

TABLE 1-4.6.4.1-3. EFFECT OF STRESSED AND UNSTRESSED THERMAL EXPOSURE ON SOLUTION HEAT TREATED AND AGED Ti-6Al-4V ALLOY[6]

Sheet Thickness, inch	Exposure Conditions: Temperature, F	Stress, ksi	Time, hours	Test Temperature, F	Tensile Properties: Ultimate Strength, ksi	Yield Strength (0.2% Offset), ksi	Elongation, %	Notch Tensile Strength, ksi
0.025	No exposure (control)			-110	197	182	7	112
(longitudinal	650	None	1000	-110	189	176	6	96
specimens)	650	25	1000	-110	199	185	3	113
	No exposure (control)			RT	171	156	6	130
	650	None	1000	RT	163	152	6	112
	650	25	1000	RT	171	164	5	119
	No exposure (control)			650	126	97	6	117
	650	25	1000	650	131	101	5	127
Bar	No exposure (control)			-110	189	174	11	--
(1-inch gage length,	Ditto			RT	165	153	14	--
transverse specimens)	"			400	130	111	13	--
	"			650	118	98	12	--
	650	25	1000	-110	190	178	11	--
	650	25	1000	RT	165	153	13	--
	650	25	1000	400	131	111	17	--
	650	25	1000	650	117	94	16	--

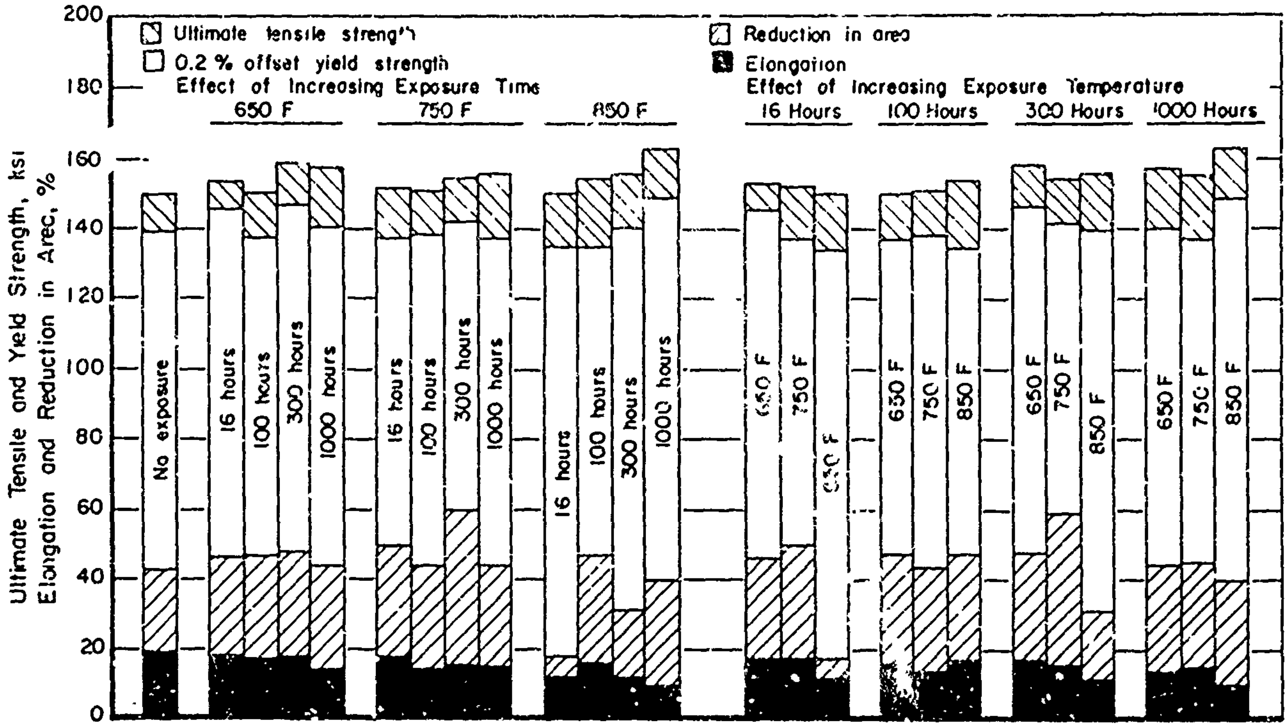


FIGURE 1-4.6.4.1-2. THERMAL STABILITY OF HEAT-TREATED Ti-6Al-4V[1]

1550 F 1 hour, water quenched; 900 F 24 hours air cooled.
Exposure stress 50 ksi

TABLE 1-4.6.4.2-1. EMBRITTLEMENT BEND-TEST RESULTS FOR Ti-6Al-4V ALLOY[1]

Bend Angle or Bend Radius for Sample A and B at Indicated Temperature[a]

Exposure Time, hours	Measurement	800 F		900 F		1000 F		1200 F		1400 F		1500 F		1600 F		1700 F		1800 F	
		A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	Angle, deg	180	180	180	180	180	180	180	180	180	180	180	65	25	25	5	3	0	0
	MBR, T	3.4	4.0	3.5	4.0	4.0	3.7	3.7	4.1	4.1	4.0	4.3	--	--	--	--	--	--	
2	Angle, deg	180	180	180	180	180	180	180	180	30	40	55	180	25	10	0	0	0	0
	MBR, T	3.3	3.5	3.4	4.0	3.8	4.1	3.7	4.2	--	--	--	4.5	--	--	--	--	--	--
5	Angle, deg	180	180	180	180	180	180	180	180	25	55	35	35	10	5	0	0	0	0
	MBR, T	3.4	3.7	3.7	4.0	3.8	4.0	3.4	4.2	--	--	--	--	--	--	--	--	--	--
10	Angle, deg	180	180	180	90	180	180	180	180	25	25	30	30	0	0	--	--	--	--
	MBR, T	3.4	3.5	3.5	--	3.7	3.5	3.4	4.1	--	--	--	--	--	--	--	--	--	--
20	Angle, deg	180	180	180	180	180	180	45	50	20	30	15	25	0	0	--	--	--	--
	MBR, T	3.4	3.7	4.0	4.0	4.1	3.4	--	--	--	--	--	--	--	--	--	--	--	--
50	Angle, deg	180	180	180	180	180	180	30	40	15	30	5	15	0	0	--	--	--	--
	MBR, T	3.4	4.1	3.5	4.4	4.4	3.4	--	--	--	--	--	--	--	--	--	--	--	--
100	Angle, deg	180	180	180	180	50	180	30	30	15	25	--	--	--	--	--	--	--	--
	MBR, T	3.4	3.1	3.4	3.7	--	3.5	--	--	--	--	--	--	--	--	--	--	--	--
200	Angle, deg	180	180	180	180	180	180	20	35	10	15	--	--	--	--	--	--	--	--
	MBR, T	3.3	2.3	3.7	3.5	4.4	3.7	--	--	--		--	--	--	--	--	--	--	--
500	Angle, deg	180	180	180	180	45	180	15	20	5	15	--	--	--	--	--	--	--	--
	MBR, T	3.3	3.1	4.1	3.5	--	4.4	--	--	--	--	--	--	--	--	--	--	--	--

(a) Values listed are either the bend angle over a 4.9T radius in degrees or the minimum radius in terms of T for 180 degree bend. A and B samples received identical treatment.

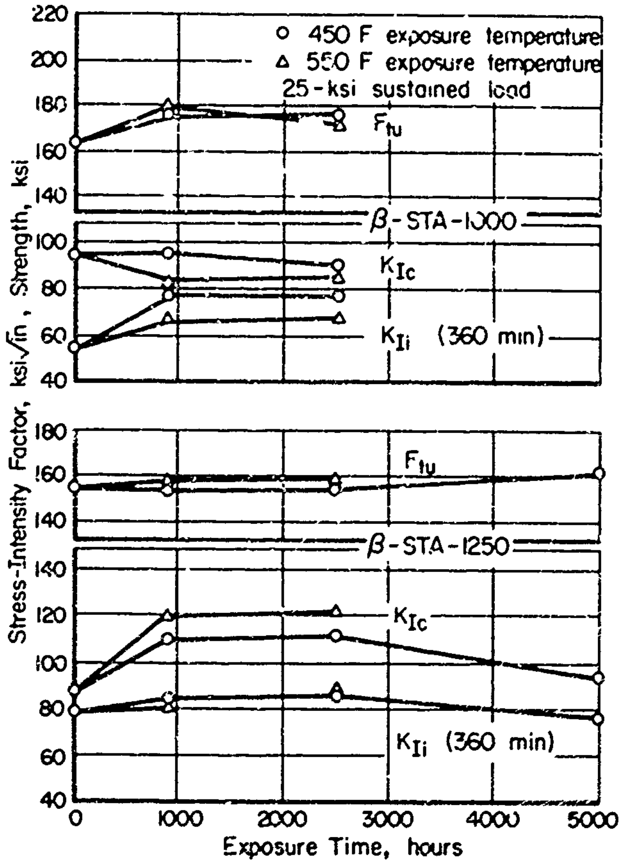


FIGURE 1-4.6.4.1-3. EFFECT OF TIME, TEMPERATURE, AND STRESS ON PROPERTIES OF Ti-6Al-4V PLATE(2)

Although Ti-6Al-4V is susceptible to stress corrosion in hot salt (NaCl) and in aqueous environments, its resistance to these forms of degradation is currently considered to be good among titanium alloys.

Susceptibility of titanium alloys to stress corrosion is evaluated by several testing techniques. Time, temperature, stress, and composition of the environment are generally considered the most important testing variables. In addition, state of stress, sample geometry, and defects within the specimen can exert significant influence. The nature of the environment, static (constant temperature, time, stress, composition, etc) or dynamic (cyclic or fluctuating, temperature, time, stress, composition, etc) also greatly influence the results of stress corrosion tests Consequently, explicit, definitive evaluation of the titanium alloys' resistance to stress corrosion requires the study of many variables. At this time, many investigations are being conducted to elucidate the stress-corrosion phenomena in titanium alloys. Based on somewhat limited data now available, Ti-6Al-4V has good resistance to environments and conditions that produce stress corrosion in other titanium compositions.

Data reflecting the resistance of Ti-6Al-4V to hot-salt stress corrosion are given in Figures 1-4.6.4.2-1, 1-4.6.4.2-2, and 1-4.6.4.2-3.

Figure 1-4.6.4.2-1 shows the effect of hot-salt stress corrosion upon the post-exposure tensile strength. In this study, sheet specimens were coated with a thick salt (NaCl) slurry, stressed to 40 ksi, and exposed at various elevated temperatures for 1000 hours. The results indicate that the strength of Ti-6Al-4V in the mill-annealed condition is not significantly affected by hot-salt exposure at temperatures as high as 540 F.

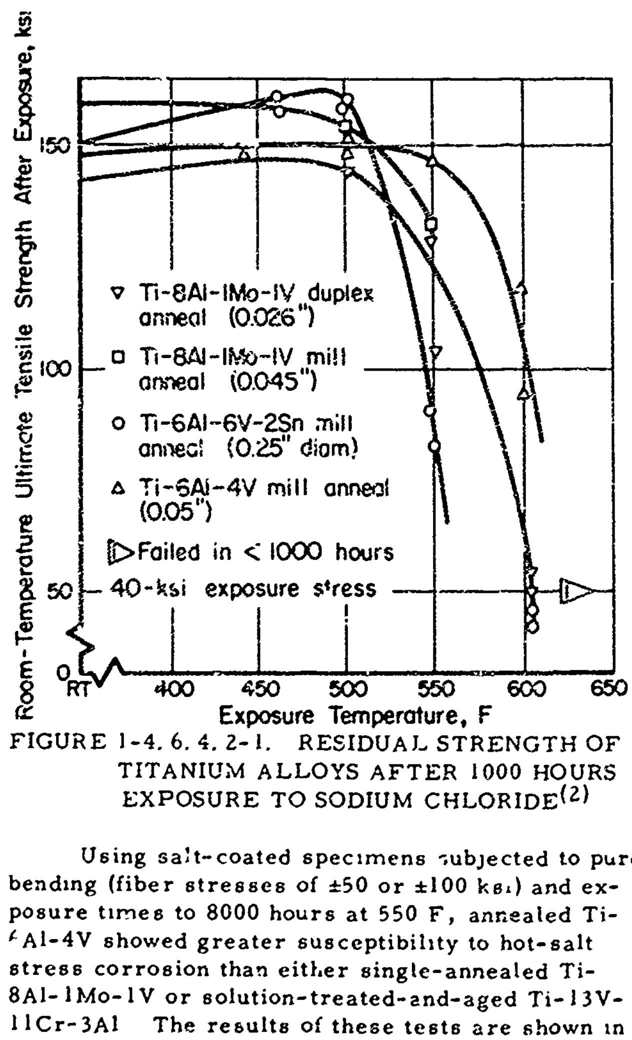


FIGURE 1-4.6.4.2-1. RESIDUAL STRENGTH OF TITANIUM ALLOYS AFTER 1000 HOURS EXPOSURE TO SODIUM CHLORIDE(2)

Using salt-coated specimens subjected to pure bending (fiber stresses of ±50 or ±100 ksi) and exposure times to 8000 hours at 550 F, annealed Ti-6Al-4V showed greater susceptibility to hot-salt stress corrosion than either single-annealed Ti-8Al-1Mo-1V or solution-treated-and-aged Ti-13V-11Cr-3Al The results of these tests are shown in Figure 1-4.6.4.2-2

A compilation of data from several sources suggests to an approximate degree the limiting combinations of exposure time, temperature, and stress above which the hot-salt stress corrosion of Ti-6Al-4V may occur The summary of these data are given in Figure 1-4.6.4.2-3.(9) That insufficient data are available to define the combination of borderline sensitivity should be emphasized.

The susceptibility of Ti-6Al-4V to accelerated crack growth in certain aqueous media at room temperature was demonstrated in 3.5 percent salt

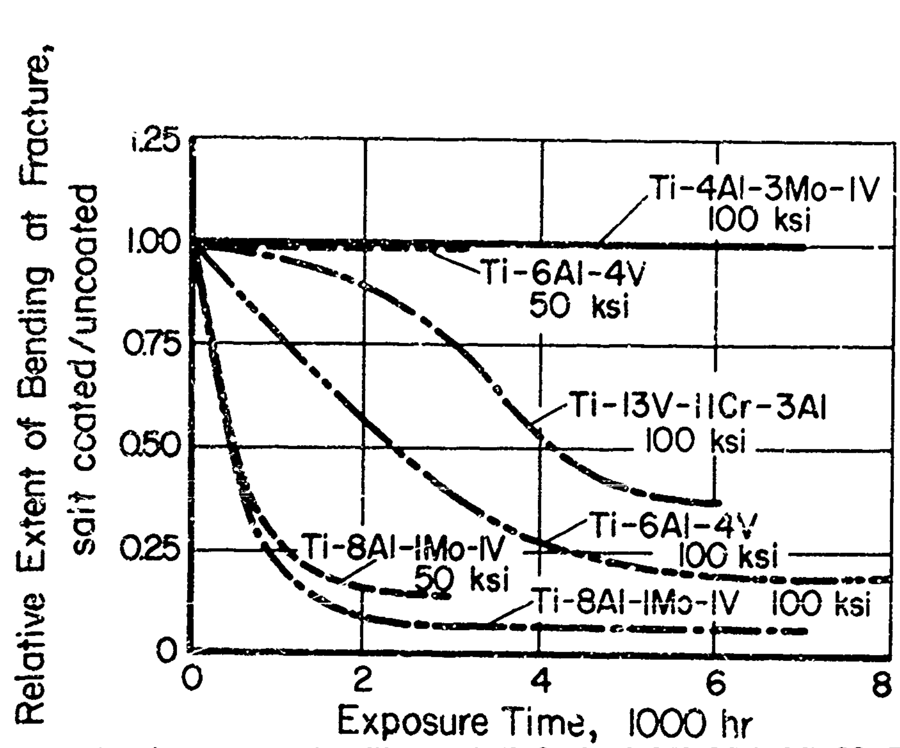


FIGURE 1-4.6.4.2-2. RELATIVE EXTENT OF BENDING OF SALT-COATED SPECIMENS AT FRACTURE AFTER VARIOUS EXPOSURE TIMES AT 550 F AND IMPOSED BENDING STRESSES[8]

Alloy	Heat Treatment
Ti-6Al-4V	1475 F 1 hr, FC to 1300 F, AC
Ti-8Al-1Mo-1V	1450 F 8 hr, FC
Ti-4Al-3Mo-1V	Aged 1050 F 4 hr
Ti-13V-11Cr-3Al	Aged 900 F 24 hr

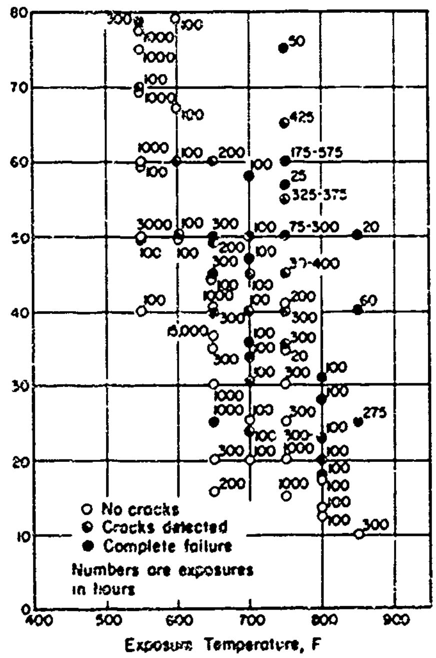


FIGURE 1-4.6.4.2-3. EFFECT OF EXPOSURE VARIABLES ON THE OCCURRENCE OF VISIBLE SALT-STRESS CORROSION IN ANNEALED AND IN SOLUTION-TREATED AND ANNEALED Ti-6Al-4V[9]

(NaCl) solution This solution has been found to produce as severe effects in promoting accelerated crack growth as any solution representative of usual operating environments for titanium alloys

Environmental crack-growth resistance is established by sustained loading of fracture-toughness samples in the salt solution to stress-intensity levels that are specific percentages of the critical stress intensity of samples tested in air The time required for specimen failure is plotted as a function of the applied stress-intensity level as illustrated in Figure 1-4.6.4.2-4.[2] The resulting curve represents the time required to propagate subcritical cracks to the critical size. For titanium alloys, subcritical crack growth does not occur below a particular stress-intensity level. Since this level was reached before 360 minutes of loading time in the illustration of Figure 1-4.6.4.2-4, the environmental crack-growth resistance parameter, K_{Ii} (360 minutes), is considered a threshold level.

The threshold stress level at which a fatigue crack of given depth in beta-processed Ti-6Al-4V becomes unstable in 3.5 percent NaCl solution is given in Figure 1-4.6.4.2-5.[2] The superior combination of strength and salt-water-crack growth

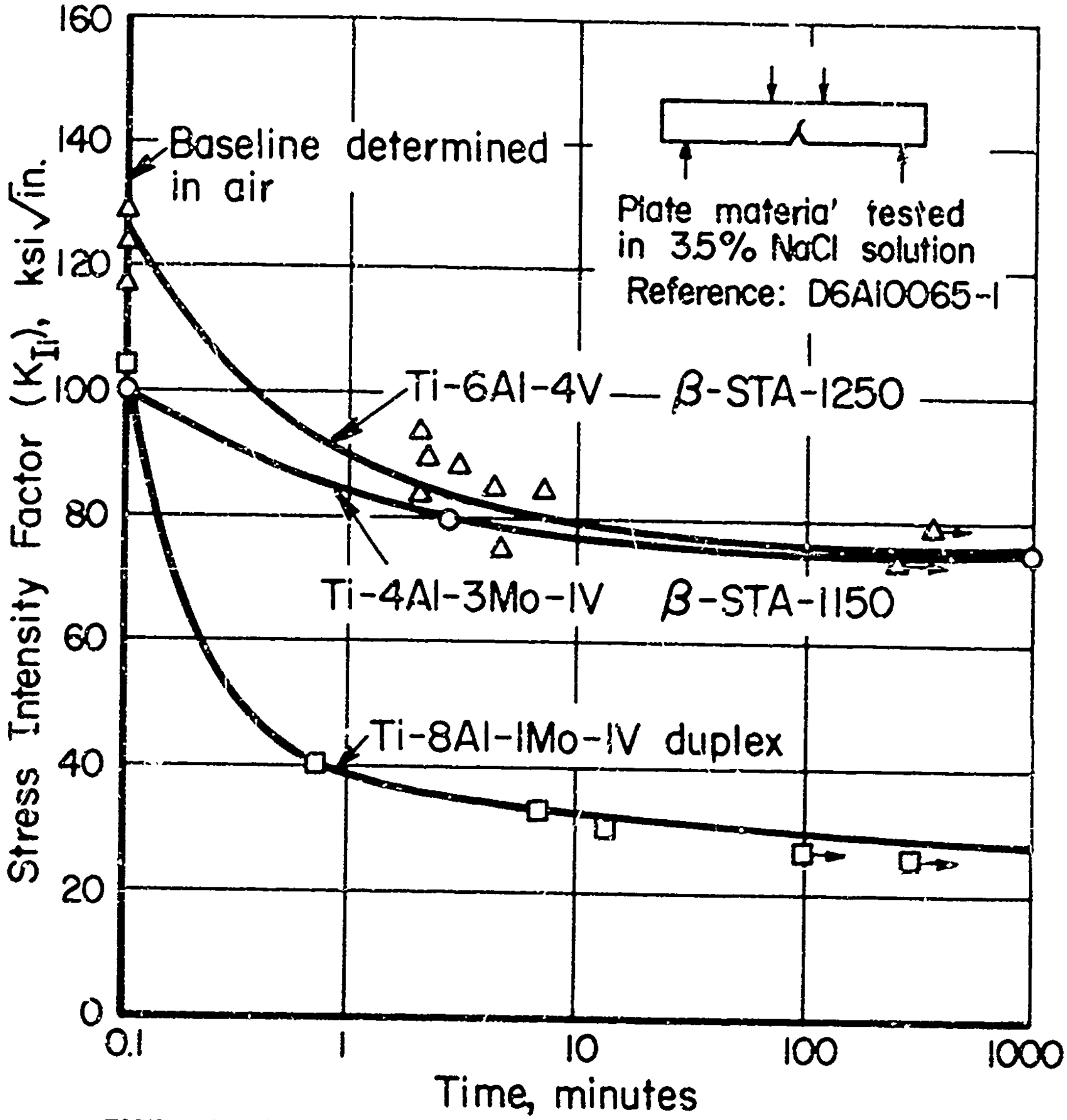


FIGURE 1-4.6.4.2-4. SALT-SOLUTION CRACK-GROWTH CHARACTERISTICS

resistance achieved in beta-processed Ti-6Al-4V, compared with conventionally (alpha-beta) processed Ti-6Al-4V, is shown for plate material in Figure 1-4.6.4.2-6.[2]

Current research[2] aimed at identification of the mechanism of environmental crack growth has suggested the following role of beta processing in improving resistance to this phenomenon. Cracking occurs in the alpha phase, and the beta phase acts to arrest the growth of the cracks. When the microstructure includes equiaxed alpha grains, characteristic of alpha-beta processed material, the beta phase is not distributed in a manner to effectively arrest crack growth. However, if the beta is primarily lamellar and randomly distributed between alpha platelets, as in the beta-processed condition, the beta phase is a very effective crack arrester.

1-4.7 REFERENCES

(1) Douglass, R. W and Holden, F C., "Compilation of Available Information on Ti-6Al-4V Alloy", TML Memorandum 148 (February, 1958).

(2) "Boeing Model 2707 Airframe Design Report, Part D, Materials and Processes", Report V2-B 2707-8, Contract FA-SS-66-5, The Boeing Company (September 6, 1966).

(3) Croan, L. S. and Rizzitano, F. S., "Influence of Forging Temperature on Mechanical Properties of Al-V Titanium Alloys", Watertown Arsenal Laboratories Report.

(4) Maykuth, D. J., "Stress Relief, Annealing, and Reactions with Atmosphere of Titanium and Titanium Alloys", TML Memorandum 118, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (May, 1957).

(5) Didderich, E. and Habraken, L., "Properties of Ti-6Al-4V Alloys with Additions of 2 and 4 Percent Cobalt", Cobalt, No. 21 (December, 1963).

(6) Compilation of data from:

(a) Freeman and Raring, "Progress Report of the NASA Special Committee on Materials Research for SST", NASA TN D-1798 (May, 1963).

(b) "Intermittent Creep and Stability Studies on SST Materials", Report AFML-TDR-64-138, GD/Ft. Worth (March, 1964).

(c) "Thick Section Fracture Toughness", The Boeing Company on Contract AF 33(657)-11461 (June, 1964).

(7) Bartlett, E. S., et al, "Thermal Stability of the Titanium Sheet Rolling Program Alloys", DMIC Report 46E (No[illegible]ber, 1958).

(8) Braks[illegible], D. N. and Heimerl, G. J., "The Relative Susceptibility of Four Commercial Titanium Alloys to Salt Stress Corrosion at 550 F", NASA TN D-2011 (December, 19[illegible]).

(9) Compilation of data from:

(a) Boyd, W. K. and Fink, F. W., "The Phenomenon of Hot Salt Stress Corrosion Cracking of Titanium Alloys", NASA CR-117 (October, 1964).

(b) "Chloride Stress Corrosion Susceptibility of High Strength Stainless Steel, Titanium Alloy, and Superalloy Sheet", Douglas Aircraft Company on Contract AF 33(657)-8543, ML-TDR-64-44, Volume II (May, 1964).

(c) Unpublished data from Lockheed Aircraft Company (November, 1964).

(d) Unpublished data from Pratt & Whitney Aircraft Company (November, 1964).

ALLOY	CONDITION	F_{tu}	F_{ty}	K_{Ic}	K_{Ii}(360 min)
Ti-4Al-3Mo-1V	β-STA-1150	160	140	95	77
Ti-6Al-4V	β-STA-1250	153	140	92	74
Ti-8Al-1Mo-1V	Mill anneal	145	135	45	30

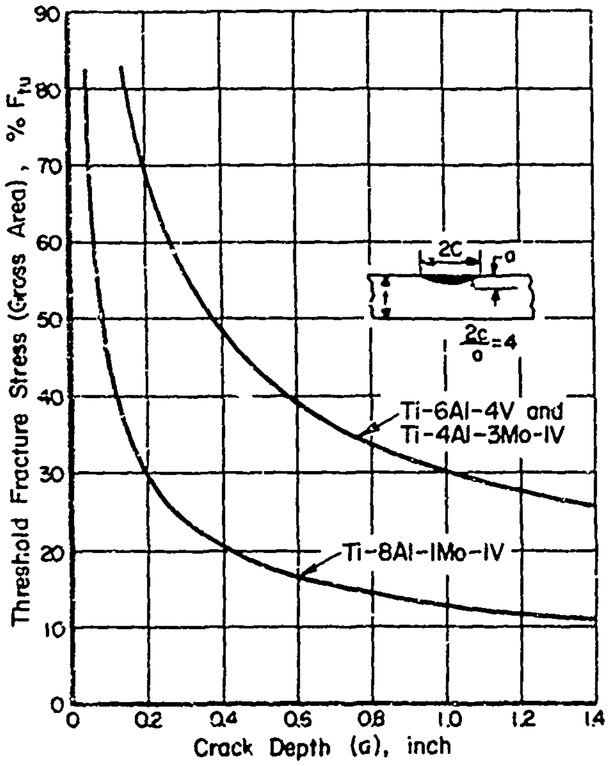


FIGURE 1-4.6.4.2-5. ENVIRONMENTAL CRACK-GROWTH RESISTANCE OF TITANIUM ALLOYS

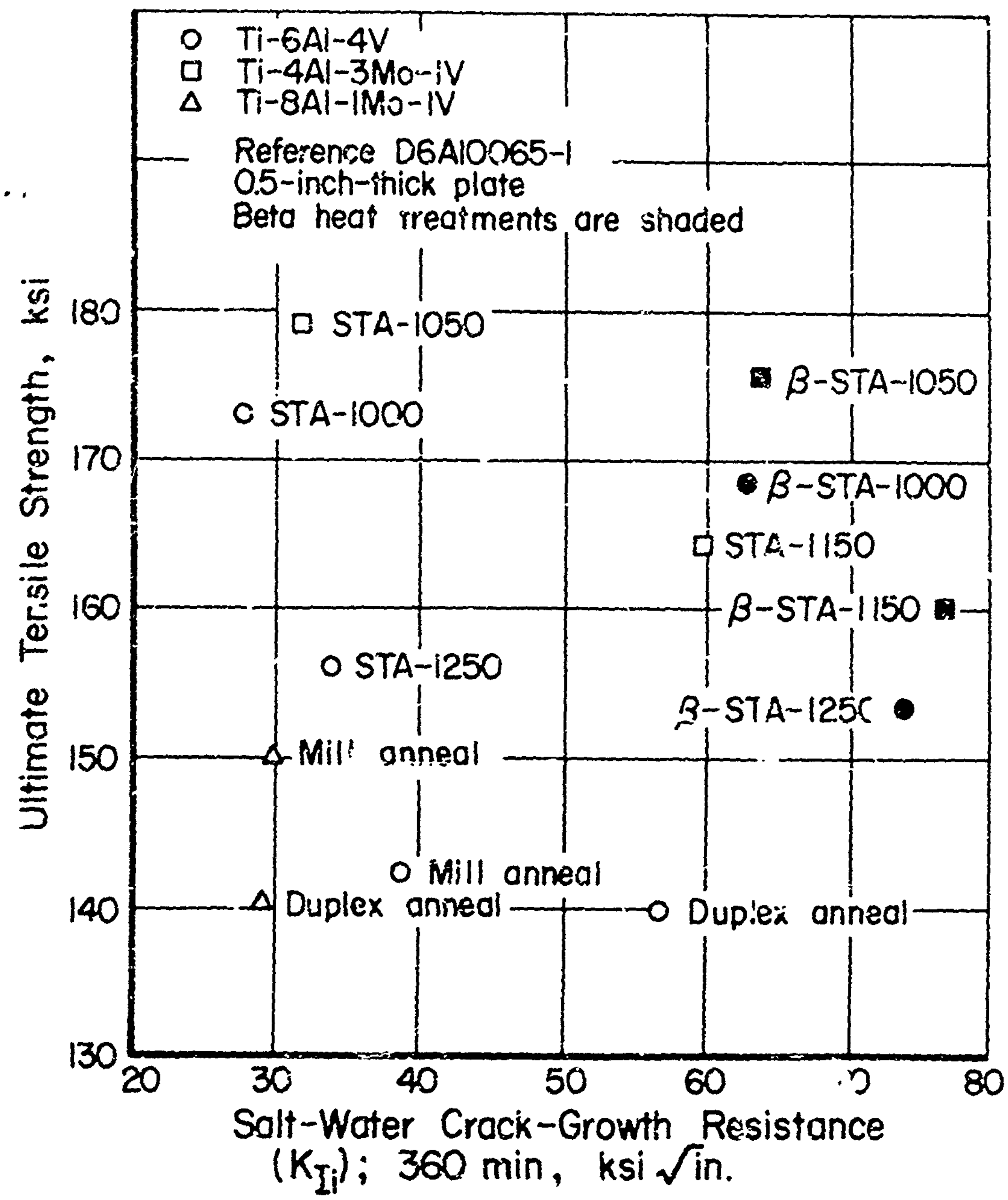


FIGURE 1-4.6.4.2-6. STRENGTH AND SALT WATER CRACK-GROWTH RESISTANCE OF TITANIUM ALLOYS[2]

1-5 Titanium Alloy Ti-6Al-6V-2Sn

1-5.0 GENERAL REMARKS

The Ti-6Al-6V-2Sn alloy is more highly alloyed with both alpha and beta stabilizers than the Ti-6Al-4V alloy and is capable of heat treatment to higher strength. It is essentially a forging alloy although plate and sheet products are utilized. It is relatively new to the titanium industry but user acceptance is high, principally due to the promise of high strength performance.

1-5.1 COMMERCIAL DESIGNATIONS

Designations	Producer	Forms Available[a]
C-125 AVT	Crucible Steel Co.	B, b, P
HA-5158	Harvey Aluminum Co.	B, b, E
No designation	Oregon Metallurgical Corp.	B
RMI-6Al-6V-2Sn	Reactive Metals, Inc.	B, b, P, S
Ti-6Al-6V-2Sn	Titanium Metals Corp.	B, b, P, S, W, E

(a) B = billet, b = bar, P = plate, S = sheet, s = strip, W = wire, E = extrusions.

1-5.2 ALTERNATE DESIGNATIONS (COMMON NAMES)

6-6-2, Titanium 6-6-2, Titanium - aluminum-tin-vanadium alloy.

1-5.3 ALLOY TYPE

Alpha-beta (rich beta content).

1-5.4 COMPOSITION, RANGE OR MAXIMUMS, %

Major Elements		Interstitial Elements	
Aluminum	5.0-6.0	Oxygen	0.12-0.20
Vanadium	5.0-6.0	Carbon	0.05
Tin	1.5-2.5	Nitrogen	0.04
Copper	0.35-1.0	Hydrogen	0.015
Iron	0.35-1.0		

1-5.5 SPECIFICATIONS

MIL-T-9035
MIL-T-46038 E
MIL-T-9046 E

1-5.6 DESCRIPTION AND METALLURGY

1-5.6.1 Composition and Structures

The Ti-6Al-6V-2Sn alloy is a relatively new alpha-beta alloy with the capability of heat treatment to very high strength levels. The nominal six percent aluminum content stabilizes the alpha phase and raises the beta transus temperature to approximately 1735 F. The two percent tin content strengthens both the alpha and beta phases, and with aluminum, aids in increasing both the room and elevated temperature strength.

Beta stabilization is accomplished by the addition of six percent vanadium and nominally 0.7 percent copper plus 0.7 percent iron. These elements are not contaminants in the Ti-6Al-6V-2Sn alloy but rather serve to help stabilize and strengthen the beta phase. The beta phase extends over the entire elevated temperature range to room temperature. The phase relationships as they exist in the Ti-6Al-6V-2Sn alloy are shown in Figure 1-5.6.1-1[1]. Acting together, the beta stabilizing elements permit heat treatment of the alloy to high strength levels by solution treatment and aging. The effect of the minor alloying conditions, copper, iron and tin, is to further strengthen the alloy: the effect of the individual elements is defined in Reference 2.

The Ti-6Al-6V-2Sn alloy is in reality an advanced Ti-6Al-4V composition. Due to the balance between alpha and beta stabilizer content, the beta to alpha-beta transus temperature remains relatively high (with respect to other compositions having this much beta content), and yet excellent workability characteristics are encountered at the high temperature because of the rich beta content. Further, the rich beta content permits deep hardenability since some beta phase does not transform during cooling from the solution heat treatment temperature. The presence of untransformed beta in large amounts to the center of thick sections permits subsequent aging response in the center sections. Ti-6Al-6V-2Sn alloy is sufficiently beta stabilized to attain heat treated properties through sections up to three inches in thickness. Of course, the heat treatment effect is stronger in the smaller sections and tapers off until annealed properties cannot be significantly improved upon in the thicker sections.

1-5.6.2 Deformation Practice and Effects

The upper temperature limit for forging Ti-6Al-6V-2Sn is dictated by proximity to the beta transus. Hot working is accomplished with greater ease above the beta transus, but in most products, a predominately acicular transformed structure forms upon cooling from the beta field.

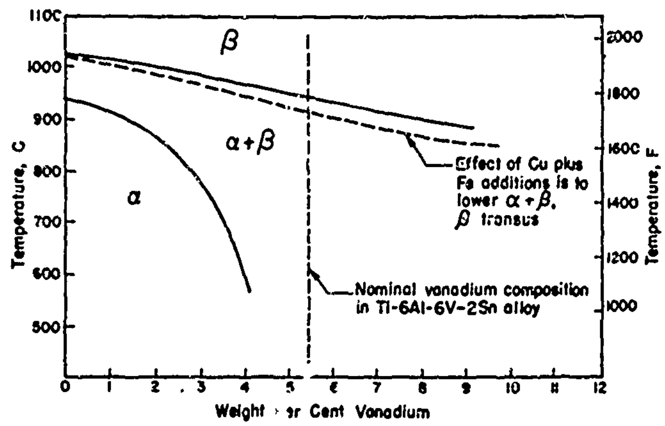


FIGURE 1-5.6.1-1. VERTICAL SECTION OF Ti-Al-V SYSTEM AT 5.5 PERCENT ALUMINUM[1]

This structure has lower strength and ductility than equiaxed structures formed by working and heat treating the metal below the beta transus. Higher working temperatures also may result in excessive grain growth and oxygen contamination and is to be limited as much as possible. Working in the beta field is permissible provided considerable additional working (about 50 percent reduction) is accomplished below the beta transus temperature which causes the equiaxed structural condition to be regained during subsequent heat treatments. Typical tensile properties after various forging reductions are given in Table 1-5.6.2-1 which show the importance of finishing with at least 50 percent reduction in the alpha-beta field.[3]

TABLE 1-5.6.2-1 TYPICAL TENSILE PROPERTIES OF Ti-6Al-6V-2Sn STOCK FORGED TO VARIOUS REDUCTIONS AND HEAT TREATED AS 3/4-INCH-DIAMETER BLANKS[(a)(3)]

Forging Reduction, %[(b)]	US, ksi	0.2% Offset YS, ksi	El, %	RA, %
10	184	172	2.5	5
30	190	182	3.2	6
50	194	187	8.3	23
60	193	189	10.1	32

(a) Solution heat treatment: 1-1/2 hours at 1630 F, water quench; age 4 hours at 1100 F, air cool.
(b) Bar stock first heated to 2000 F and air cooled to room temperature. The forging reductions indicated were at 1725 F and were followed by water quenching.

The lower temperature limit for forging is based on the ability of the metal to deform uniformly without cracking or cold shearing. It is also a function of the type of forging operation involved and equipment power considerations. The lower limit is around 1550 F. Above this temperature, the Ti-6Al-6V-2Sn alloy forges readily. Since the beta transus temperature is about 1735 F, the full forging range is therefore 1550 to 1725 F. However, a 1600 to 1650 F range is suggested for most forging operations. The finished forging, after an appropriate heat treatment, should have a structure of primary alpha phase in a matrix of beta phase[4].

Very few data are available showing the effect of cold work on the properties of Ti-6Al-6V-2Sn alloy. In fact, the alloy would not usually be cold worked to make parts. Nevertheless such operations as shear forming have been briefly examined where it was found that good properties can be restored to the cold worked metal by the use of an annealing heat treatment as shown below[3,5].

Condition, Heat Treatment	UTS, ksi	0.1% Offset YS, ksi	El, %	RA, %
As shear formed	162	142	7	16
1100 F, 1/2 hour, AC	169	162	12	33
1100 F, 4 hours, AC	169	162	12	32
1625 F, 1/2 hour, WQ + 1100 F, 4 hours, AC	176	170	3	8

It is apparent that adjustments in solution heat treatment and aging cycles would be needed if a very high strength condition after cold working was required.

1-5.6.3 Heat Treatment Practice and Effects

1-5.6.3.0 General Remarks

The Ti-6Al-6V-2Sn alloy may be used in either the annealed condition or, since it is an alpha-beta alloy with a rich beta content, in a very high strength condition achieved by solution heat treatment and aging. Ductility and toughness are correspondingly lower with the higher strength conditions.

1-5.6.3-1 Stress-Relief Annealing

A thermal treatment of 2 hours at 1100 F followed by air cooling to room temperature is the

treatment recommended by the producers for stress-relief annealing the Ti-6Al-6V-2Sn alloy. No data are available showing the relaxation characteristics of residual stress in this alloy during stress-relief treatments.

1-5.6.3.2 Annealing

The Ti-6Al-6V-2Sn alloy is one of the strongest titanium grades available in the annealed condition which consists of about 2 to 8 hour exposure at 1300 to 1400 F followed by air cooling. Another annealing treatment recommended is 1/2 hour exposure at 1330 to 1550 F, furnace cool to 1100 F, and air cool to room temperature. In these annealed conditions, the metal has fair thermal and stress stability (up to about 600 F) and has better fracture toughness than solution heat treated and aged Ti-6Al-6V-2Sn. Typical annealed mechanical properties showing also the effect of section size are given in Table 1-5.6.3.2-1[6].

With respect to the various annealing treatments recommended, it has been suggested[7] that annealed Ti-6Al-6V-2Sn alloy would have better elevated-temperature stability if the annealing treatment included furnace cooling from the recrystallization temperature to an intermediate temperature such as is done with the Ti-6Al-4V alloy. Annealed and furnace cooled tensile properties of Ti-6Al-6V-2Sn sheet (0.097 inch) were found to be[3]:

	UTS, ksi	YS, 0.2% Offset ksi	El, %
Avg. of 4 longitudinal specimens	152	143	14
Avg. of 3 transverse specimens	157	150	12

(Annealed at 1525 F for 3/4 hour, furnace cooled to 1100 F, then air cooled.)

The ductility of weldments in Ti-6Al-6V-2Sn alloy is poor unless a postweld annealing treatment is used. Solution heat treatment followed by water quenching does not improve weld ductility and subsequent aging of such conditioned material results in weld metal embrittlement. Solution of the weld metal ductility problem is possible in some applications by using an annealing treatment. The treatment of 4 hour exposure at 1340 F, followed by air cooling has been recommended[4]. Annealed strengths are of course lower than aged strengths but usable ductility and toughness can be obtained in weldments using this technique.

1-5.6.3.3 Strengthening Heat Treatments

The ultimate strengthening of the Ti-6Al-6V-2Sn alloy is based upon a simple age hardening reaction. Beta phase stabilized by solution heat treatment in the alpha-beta field is retained to room temperature by quenching. Upon reheating to some lower temperature in the alpha-beta field, the beta phase partially transforms isothermally to the alpha phase. The fine alpha precipitate that forms during aging is the constituent that promotes the strengthening of the alloy over the base annealed condition.

1-5.6.3.3.1 Solution Annealing

The recommended solution heat treatment temperature for Ti-6Al-6V-2Sn is 1650 ± 25 F. About 30 percent primary alpha, balance beta phase, is found in the microstructure after this treatment. Water quenching is the standard method of terminating solution heat treatment although fast air cooling achieved by forced air stream may be satisfactory for thin section material since the beta phase in this alloy is fairly stable. The effect of solution temperature on subsequently aged tensile properties is shown by the data given in Table 1-5.6.3.3.1-1[2].

1-5.6.3.3.2 Aging Heat Treatments

For a given solution heat treatment, the selection of an aging cycle is based on the strength level desired. Low aging temperatures, on the order of 900 to 1000 F are associated with higher strength and lower ductility. High aging temperatures, in the 1100 to 1200 F range, promote lower strength and higher ductility levels.

The effect of various aging treatments on the tensile properties of Ti-6Al-6V-2Sn plate, press forged from 100 degrees below the beta transus of 1780 F and water quenched (no intermediate solution heat treatment between alpha-beta forging and aging), is shown in Figure 1-5.6.3.3.2-1[3]. In Figure 1-5.6.3.3.2-2, the effect of the same treatments on Charpy impact absorption energy is shown, while the effects of various aging treatments on Charpy values obtained over a range of test temperatures are shown in Figure 1-5.6.3.3.2-3[9]. Typical solution treated plus aged room temperature tensile properties obtained after a variety of heat treatments are given in Table 1-5.6.3.3.2-1[8,10].

For optimum mechanical properties of aged material, consistent with good thermal and stress stability, an aging treatment of from 4 to 8 hours at 1000 to 1150 F, followed by air cooling is recommended.

1-5.6.4 Stability

Very few data are available depicting the stability of the Ti-6Al-6V-2Sn alloy. The thermal stability of this alloy appears to be dependent upon heat treated condition and probably fabrication history. The chemical stability of the alloy is practically undocumented, although a reasonable first assumption would be that it is similar to the Ti-6Al-4V alloy.

TABLE 1-5.6.3.3.1-1. EFFECT OF SOLUTION TEMPERATURE ON THE AGED ROOM-TEMPERATURE TENSILE PROPERTIES OF Ti-6Al-6V-2Sn BARS(2)

(Alpha-beta to beta transus ~1750 F.)

Solution Temperature,(a) F	UTS, ksi	YS 0.2% Offset, ksi	El, %	RA, %	Modulus, 10^3 ksi
1600	173	157	10	27	17.3
1650	176	161	12	27	17.4
1700	179	164	3	6	16.3
1725	171	159	3	4	16.3
1725	166	157	6	10	16.2

(a) For 1 hour followed by water quenching.
(b) Aged for 1 hour at 1100 F, air cooled.

TABLE 1-5.6.3.2-1. TYPICAL MECHANICAL PROPERTIES OF ANNEALED Ti-6Al-6V-2Sn ALLOY AT VARIOUS BAR STOCK AND SPECIMEN DIAMETERS(6)

Specimen Diameter, inches	UTS, ksi	0.2% Offset YS, ksi	El, %	RA, %	NTS, ksi	NTS/YS Ratio
0.113	157	142	20	40	-	--
0.160	146	130	19	44	226	1.64
0.225	---	---	--	--	220	--
0.252	146	135	20	44	-	--
0.357	148	140	19	43	210	1.53
0.505	147	142	17	43	190	1.38
0.714	---	---	--	--	179	--
1.130	138	126	14	34	-	--
1.600	149	135	16	25	150	1.09
2.250	---	---	--	--	124	--
2.520	143	---	10	31	-	--
3.570	---	---	--	--	102	--

1-5.6.4.1 Thermal Stability

The thermal stability of both annealed and aged Ti-6Al-6V-2Sn bar was determined in a series of creep test exposures. The test data obtained after various exposure conditions of time, temperature, and stress are given in Table 1-5.6.4.1-1, while a summary of the tensile-property data obtained after exposure is given on the next page(7).

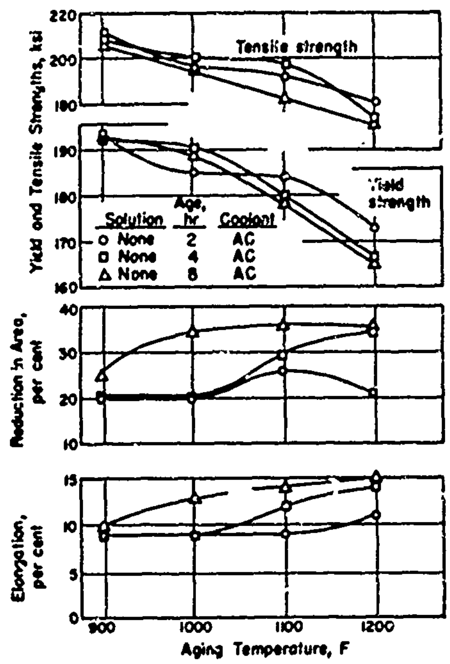


FIGURE 1-5.6.3.3.2-1. EFFECT OF AGING TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-6V-2Sn PLATES(3)

2-inch-diameter, 5-inch-long billet reduced 87%, press forged to 5/8-inch plate from beta, 100 F W Q, beta transus 1780 F.

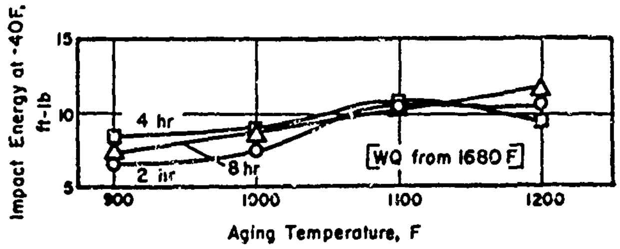


FIGURE 1-5.6.3.3.2-2. EFFECT OF AGING TREATMENT ON THE IMPACT STRENGTH OF Ti-6Al-2Sn PLATE(3)

(Charpy V-notch specimens).

The exposure of annealed bars resulted in an increase in both tensile and yield strengths with a corresponding decrease in ductility. These results undoubtedly reflect the occurrence of an aging reaction of the air-cooled (from the annealing temperature) structure. The investigators suggested that furnace cooling from the annealing temperature would remedy this reaction. This hypothesis is strengthened by the results obtained on age hardened bars. Here the signs of instability do not show up even in long time exposure (>1000 hours) at 600 or 700 F, indicating a metallurgically stable structure. The data indicate that the aging reaction may continue however, when exposure temperatures (800 F) approach closer to the aging temperature.

Exposure Temperature,[a] F	Room-Temperature Tensile Properties: US, ksi	0.2% Offset YS, ksi	El, in 1 Inch, %	Reduction in Area, %
	Annealed Bars			
None	160.7	153.2	17.0	50.8
600	188.9	157.6	13.1	32.3
700	193.1	170.6	12.1	26.4
800	185.4	177.2	12.8	30.5
	Solution-Treated and Aged Bars			
Not exposed	187.2	182.5	10.5	30.7
600	195.9	186.0	8.6	21.1
700	190.3	182.8	11.1	26.3
800	199.5	190.5	6.8	12.7

(a) See Table 1-5.6.4.1-1 for exposure times and stress levels.

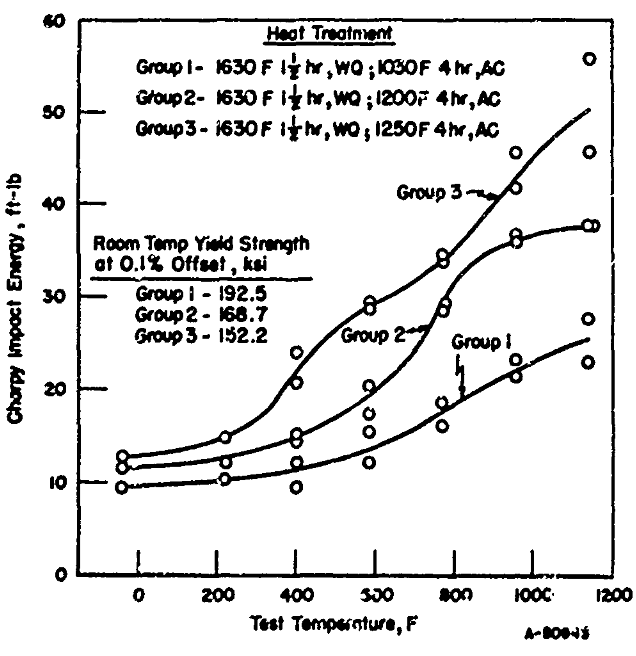


FIGURE 1-5.6.3.3.2-3. CHARPY IMPACT ENERGY VERSUS TEST TEMPERATURE FOR THREE AGING TEMPERATURES Ti-6Al-6V-2Sn(9)

(Standard specimens).

The data generated also showed that an alpha-beta alloy having a rich beta content such as in Ti-6Al-6V-2Sn does not maintain strength in long-time, elevated-temperature exposure as well as lean beta compositions such as Ti-6Al-4V. Additional data showing further the thermal stability of Ti-6Al-6V-2Sn products are given in Table 1-5.6.4.1-2[4].

1-5.6.4.2 Chemical Stability

There is a paucity of data available that might be used to describe the chemical stability of Ti-6Al-6V-2Sn alloy. However, it is believed that the chemical behavior of this alloy would not be materially different than that of the Ti-6Al-4V alloy, especially in elevated temperature exposures involving oxidation or salt-stress corrosion.

1-5.7 REFERENCES

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(4) Broadwell, R., "Properties of Ti-6Al-6V-2Sn", Titanium Engineering Bulletin No. 10, TMCA, Approximately 1963.

(5) Colton, R. M. and Malatesta, W. C., "Flo-turning and Welding Characteristics of Ti-6Al-6V-2Sn Alloy", WAL-TN-405.2/6, December, 1959.

(6) DeSisto, T. S., et al., "The Influence of Section Size on the Mechanical Properties and Fracture Toughness of 7075-T6 Aluminum, Ti-6Al-6V-2Sn, and AISI 4340 Steel", AMRA TR 64-05, February, 1964.

(7) Seagle, S. R., "Elevated Temperature Tensile and Creep Properties of Ti-6Al-6V-2Sn Bar", Reactive Metals Report 1006R445, July, 1963.

(8) Dethloff, R. C., "Rocket Motor Case Development", QPR No. 15 on Ordnance Contract, The Budd Company, September, 1961.

(9) Lannelli, A. A. and Rizzitano, F. J., "Charpy Impact Tests of 4340 Steel and 6Al-6V-2Sn Titanium Alloy, Using Standard and Thin Charpy Specimens", WAL TR-112.5/3, January, 1962.

(10) Hiner, J. M., "Development of 6Al-6V-2Sn Titanium Alloy Pressure Vessel", Menasco Report A235-1, April, 1960.

TABLE 1-5.6.3.3.2-1. EFFECT OF DIFFERENT HEAT TREATMENTS ON THE TENSILE PROPERTIES OF Ti-6Al-6V-2Sn TITANIUM ALLOY[(a)](8, 10)

Heat Treatment	Ultimate Tensile Strength, ksi	Yield Strength (0.2% Offset), ksi	Elongation in 4D, %	Reduction in Area, %
1625 F 1/2 hr, WQ + 1000 F 8 hr	193	183	6.8	17.2
1625 F 1/2 hr, WQ + 1000 F 16 hr	192	183	5.5	12.5
1625 F 1/2 hr, WQ + 1025 F 4 hr	194	185	6.5	16.5
1625 F 1/2 hr, WQ + 1025 F 8 hr	191	187	7	14.5
1625 F 1/2 hr, WQ + 1025 F 16 hr	190	182	8.2	21.7
1625 F 1/2 hr, WQ + 1100 F 4 hr	186	177	9	20.7
1625 F 1/2 hr, WQ + 1100 F 8 hr	183	174	3.7	20.0
1625 F 1/2 hr, WQ + 1100 F 16 hr	179	172	11.8	26.9
1630 F 1/2 hr, WQ + 1150 F 16 hr	192	184	7.5	17.0
1650 F 1/2 hr, WQ + 1050 F 1 hr	218-219	211-212	0.5-2.5	--(b)

(a) Data generated using specimens cut from forgings (thin section).
(b) Data generated on 0.085-inch sheet (Reference 8).

TABLE 1-5.6.4.1-2. STABILITY OF Ti-6Al-6V-2Sn AFTER PROLONGED EXPOSURE TO ELEVATED TEMPERATURES[(a)](4)

Exposure Condition			Room Temperature Properties After Exposure			
Temperature, F	Stress, ksi	Time, hours	Yield Strength 0.2% Offset, ksi	Ultimate Tensile Strength, ksi	Elongation in 4D, %	Reduction In Area, %
Unexposed forged bar stock			184.8	193.6	9.0	38.5
850	55	150	188.3	199.8	9.0	25.4
850	55	150	191.2	201.8	8.0	26.1
850	55	150	204.1	204.1	7.0	20.8
850	45	150	189.2	197.6	10.0	35.9
800	55	150	194.7	204.5	7.0	21.3
800	45	150	183.8	195.9	9.5	31.6
750	65	150	187.6	199.4	8.0	33.6
750	65	150	183.4	194.4	9.0	39.2
Unexposed extrusion			169.0	180.2	11.0	24.0
700	30	1000	167.6	182.3	11.0	22.6

(a) Heat treatment: 1650 F 1 hour, WQ + 1050 F 4 hours, AC.

TABLE 1-5.6.4.1-1. EFFECT OF CREEP-TEST EXPOSURE OF Ti-6Al-6V-2Sn BAR(7)

Temperature, F	Stress, ksi	Time, hr	Total Deformation, %	Properties After Creep: Ultimate Tensile Strength, ksi	Yield Strength (0.2% Offset), ksi	Elongation in 1 Inch, %	Reduction in Area, %
			Annealed Bars				
600	88	149	.450	193.0	161.0	13.5	31.6
	60	28	.294	178.0	148.5	15.5	44.6
	25	258	.240	192.0	159.0	12.0	30.5
	15	955	.176	192.5	162.0	11.5	22.6
			Avg	188.9	157.6	13.1	32.3
700	40	148	.318	192.5	167.5	11.0	22.6
	25	306	.199	193.0	169.5	12.0	26.4
	15	119	.179	190.0	166.0	15.0	38.9
	20	630	.120	194.5	176.5	11.0	24.0
	10	1,438	.152	195.7	173.4	11.5	20.1
			Avg	193.1	170.6	12.1	26.4
800	15	144	.300	183.0	175.0	12.0	30.1
	12.5	388	.268	183.7	176.4	13.0	31.1
	10	357	.176	186.5	178.0	13.0	29.7
	8	815	.217	188.5	179.5	13.[illegible]	31.1
			Avg	185.4	177.2	12.8	30.5
			Aged Bars				
600	125.0	143	.749	194.2	191.6	9.0	23.7
	100.0	191	.217	188.0	178.0	11.0	32.0
	81.5	288	.214	202.0	186.5	7.0	13.8
	70.0	1,392		199.5	188.0	7.5	14.7
			Avg	195.9	186.0	8.6	21.1
700	65.0	143	.481	199.5	184.0	7.5	14.5
	50.0	386	.430	191.0	188.5	9.0	18.6
	37.5	217	.262	184.0	178.0	14.0	45.8
	17.5	1,144	.173	186.5	180.5	14.0	26.4
			Avg	190.3	182.8	11.1	26.3
800	45.0	142	.765	194.4	180.8	5.5	9.5
	35.0	192	.525	195.5	187.5	9.0	17.2
	20.0	461	.365	195.0	188.5	6.0	11.4
	10.0	1,301	.156	214.0	205.0	Broke outside gage	
			Avg	199.5	190.5	6.8	12.7

1-6 Titanium Alloy Ti-13V-11Cr-3Al

1-6.0 GENERAL REMARKS

The Ti-13V-11Cr-3Al alloy is the only beta-titanium alloy of commercial importance. It is heat treatable to very high strength levels from the annealed/solution-treated (synonymous) condition by aging. In the annealed condition, the beta alloy is very formable.

1-6.1 COMMERCIAL DESIGNATIONS

Designations	Producer
B-120VCA	Crucible Steel Company
No designation	Oregon Metallurgical Corporation
RMI-13V-11Cr-3Al	Reactive Metals, Incorporated
Ti-13V-11Cr-3Al	Titanium Metals Corporation

Forms Available(a)
B, b, P, W
B
B, b, P, S,
B, b, P, S, W, E

(a) B = billet, b = bar, P = plate, S=sheet, s = strip, W = wire, E = extrusion

1-6.2 ALTERNATE DESIGNATIONS (COMMON NAMES)

B-120, 13-11-3, VCA, the beta alloy.

1-6.3 ALLOY TYPE

Beta (metastable)

1-6.4 COMPOSITION RANGE OR MAXIMUMS, %

Major Elements		Interstitial Elements	
Aluminum	2.50-4.00	Carbon	0.05-0.10
Vanadium	12.50-14.50	Oxygen	0.20
Chromium	10.00-12.00	Nitrogen	0.05-0.08
Iron	0.35	Hydrogen	0.015 bar

1-6.5 SPECIFICATIONS

AMS-4917, MIL-T-9046E

1-6.6 DESCRIPTION AND METALLURGY

1-6.6.1 Composition and Structure[1]

The beta alloy contains relatively large amounts of beta-stabilizer elements and relatively small amounts of alpha-stabilizer elements. The alloy is classified as a beta alloy since the structure of the metal is entirely beta phase (body-centered cubic crystal lattice) at room temperature after annealing from above the beta-transus temperature. This structure is easily obtained at room temperature even after very slow cooling rates because of the beta-stabilizing characteristics of the high vanadium and chromium alloying elements.

The effect of variable chromium content on the phase relationships of the Ti-13V-11Cr-3Al alloy is shown in Figure 1-6.6.1-1. At the nominal composition, Ti-13V-3Al base plus 11 percent chromium and low oxygen content, the alloy is hypoeutectoidal with a beta transus between 1200 and 1300 F. The high vanadium content contributes to the stabilization of the beta phase to this low temperature, but it does not contribute to the titanium-chromium eutectoid relationship.

The effect of variable aluminum content is shown in Figure 1-6.6.1-2. Increasing aluminum content stabilizes the alpha phase, thus raising the beta-transus temperature. Without aluminum, the alloy would have a very low beta transus. The nominal 3 percent aluminum addition results in the aforementioned 1200 to 1300 F beta-transus temperature when oxygen content is low. The beta transus temperature is located at higher temperatures with increasing oxygen content. The commercial grade usually contains about 0.15 percent oxygen and has a beta-transus temperature above 1300 F.

While the beta phase is thermodynamically stable down to about 1200 F with low oxygen content, the decomposition of the beta is very sluggish at still lower temperatures. The TTT diagram illustrating this sluggishness of the beta phase is given in Figure 1-6.6.1-3. Other investigators have found slight deviations from the transition conditions indicated in Figure 1-6.6.1-3. However, variations in experimental technique and material composition would account for the small differences from the general relationships shown. The decomposition products of the beta phase are the alpha phase and the intermetallic compound, $TiCr_2$. The omega phase is believed to be a decomposition product of the beta phase also. However, the conditions for the occurrence of omega have not been defined for the alloy, and so are not shown. Omega is believed to be unstable and to decompose very rapidly above about 1000 F. The slow decomposition of the sluggish beta phase permits the use of a wide variety of heat treatments to control the properties of the alloy.

1-6.6.2 Deformation Practice and Effects

Because of the difficulties encountered in deforming Ti-13V-11Cr-3Al alloy at high strain rates, press forging is usually used to form this alloy. Pratt & Whitney Aircraft Company investigations have revealed that at forging temperatures at 1750 F or below a 50 percent reduction

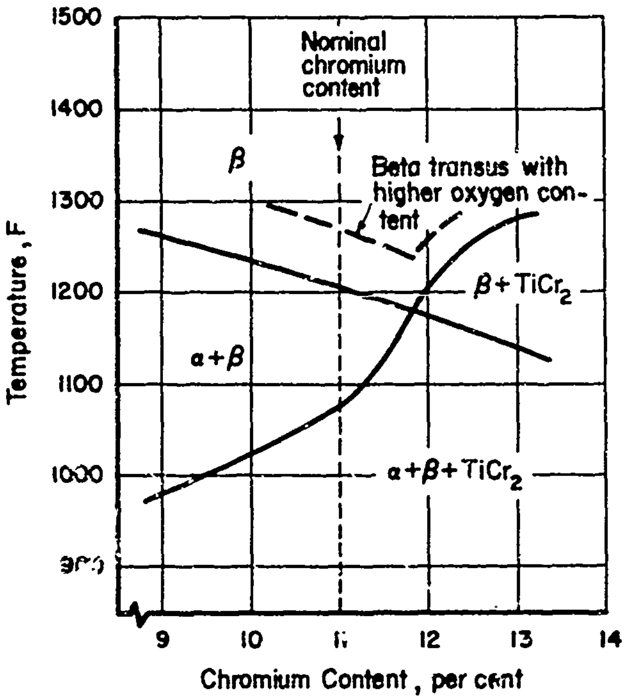

FIGURE 1-6.6.1-1. PHASE DIAGRAM OF B-120VCA ALLOY WITH VARIABLE CHROMIUM CONTENT ($Ti-13V-Cr-3Al-0.05\ O_2$)(1)

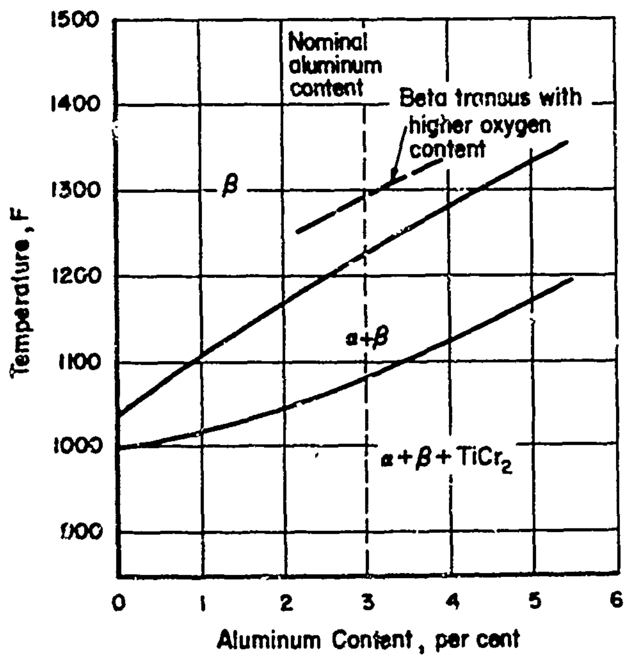

FIGURE 1-6.6.1-2. PHASE DIAGRAM OF B-120VCA ALLOY WITH VARIABLE ALUMINUM CONTENT ($Ti-13V-11Cr-Al-0.05-O_2$)(1)

in the final operation results in a structure capable of meeting subsequent aged strength requirements (180 ksi yield strength)(2). While these deformation temperatures are above the beta transus temperature, the cooled structure is not acicular because equiaxed beta phase is retained to room temperature, due to the high alloy content. It is retained from still higher forging temperatures too, but subsequent aged properties are not so good, probably because of excessive grain growth and contamination at the higher forging temperature. Pratt & Whitney also found that a 1450 F solution-annealing treatment following the forging operation was beneficial in reducing the spread in strength values from place to place within the forging.

The Ti-13V-11Cr-3Al alloy normally is fabricated to flat-rolled products in the beta-phase field. (The final fabrication of sheet by rolling to finish gages is often done cold to obtain improved flatness and gage uniformity.) After fabrication, the metal is annealed in the beta field for 1/4 to 1/2 hour at 1400 to 1450 F, followed by air cooling.

While it is known that the uniform elongation of Ti-13V-11Cr-3Al alloy at room temperature is fairly low, bend ductility is excellent. Also, flow stresses at strain rates typical of stretch forming are high. Thus, while such operations as stretch forming at room temperature may be difficult even on fully annealed material, operations such as involve bending are easily performed. The effect of cold work on the subsequent properties of Ti-13V-11Cr-3Al are shown in Figure 1-6.6.2-1(1) The effect of cold work on annealed and aged material (strained after annealing and prior to aging) is shown in Figure 1-6.6.2-2.(1)

Moderately elevated temperatures may be used to enhance the forming characteristics of the beta alloy. For example, uniform elongation of annealed Ti-13V-11Cr-3Al is increased as shown below:

Temperature, F	Uniform Elongation %
RT	5-8
100	10-11
200	~13
400	~14

Elongation decreases somewhat between 400 and 800 F, then increases rapidly above 800 F. With respect to the effect of warm working after solution treatment on the subsequent aged properties of the beta alloy, there is little difference between warm working and cold working. Both operations serve to produce favorable distribution of the alpha precipitate and accelerate the aging response as illustrated in Figure 1-6.6.2-3.(1) The degree of acceleration is inversely proportional to working

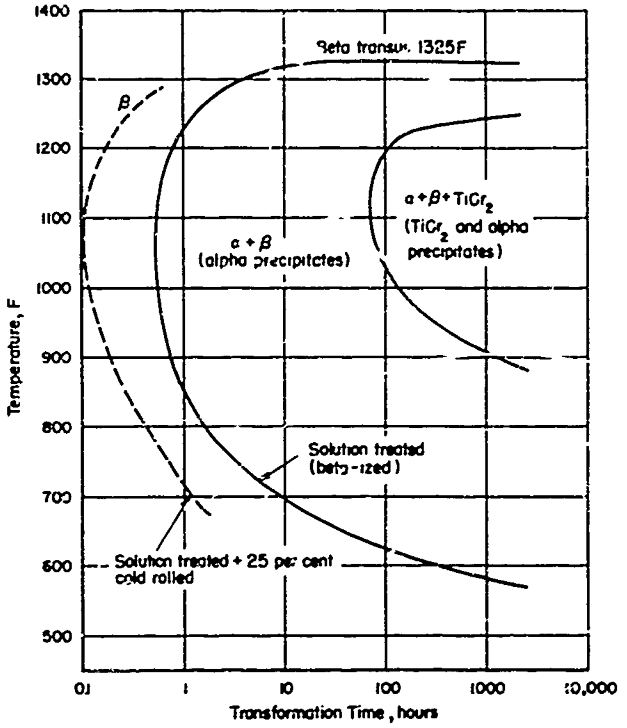

FIGURE 1-6.6.1-3. TTT DIAGRAM FOR Ti-13V-11Cr-3Al AS DETERMINED BY METALLOGRAPHIC TECHNIQUE (Ti-13V-11Cr-4Al-0.15 O_2)[1]

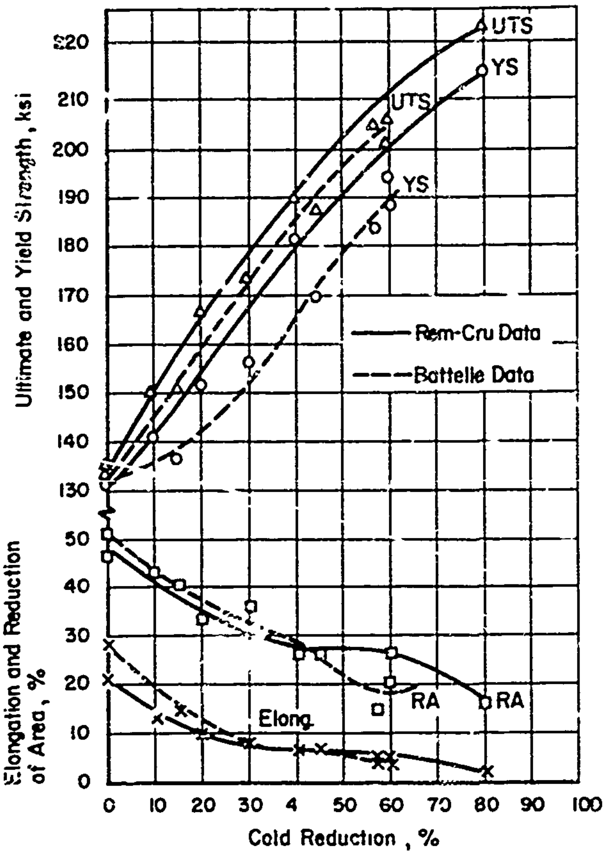

FIGURE 1-6.6.2-1. EFFECT OF COLD WORK ON TENSILE PROPERTIES OF ANNEALED Ti-13V-11Cr-3Al SHEET[1]

temperature and directly proportional to the amount of cold or warm work introduced in the material. Of course, working at temperatures considerably above the relatively low beta-transus temperature of Ti-13V-11Cr-3Al alloy will have little effect on subsequent properties, since the annealed condition is effectively maintained during the operation.

1-6.6.3 Heat-Treatment Practice and Effects

1-6.6.3.0 General Remarks

Normal air cooling from the annealing temperature retains the beta-phase structure. Thus, the term "annealed condition" is synonymous with the term "solution-treated condition". In the annealed solution-treated condition, the beta retained at room temperature is metastable. That is, it can be decomposed by thermal treatment. The precipitation products formed during such an aging treatment, alpha and $TiCr_2$, cause the structure to be stronger and less ductile than the precipitate-free structure. A wide variety of heat treatments to result in the age-hardened condition are possible.

1-6.6.3.1 Stress-Relief Annealing

The temperatures used to stress relieve the Ti-13V-11Cr-3Al alloy are in the aging temperature range for the material, although time of exposure for stress relief is shorter than for aging. The bulk of the stress-relief annealing data available is for the stress-relief annealing of weldments. TMCA reports that fusion weldments in 0.250-inch plate may be stress relieved to zero residual stress levels by the following treatments:[3]

4 hours at 900 F, AC
1 hour at 1000 F, AC
<1/2 hour at 1100 F, AC
<1/2 hour at 1200 F, AC

Pratt & Whitney Aircraft Company found that a 550 F preheat on material to be welded reduced residual tensile stresses in the weldment by as much as 60 percent.[4] They also found that cold rolling the weldments reduced longitudinal residual tensile stress (20 percent cold reduction was required for zero residual stress). Fifteen-minute, 1400 F, or 5-minute, 1800 F, treatments resulted in weld embrittlement. However, for stress-relief annealing of material other than weldments, a 1400 to 1450 F reannealing treatment would be satisfactory.

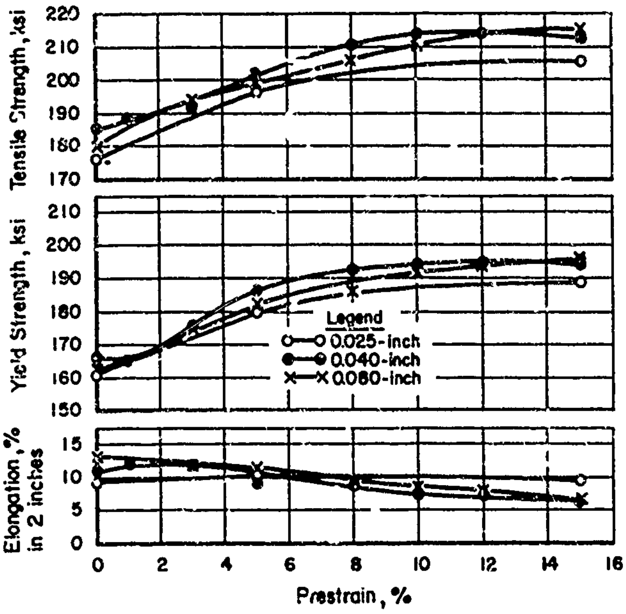

FIGURE 1-6.6.2-2. EFFECT OF STRAINING AFTER SOLUTION TREATMENT ON THE SUBSEQUENT AGED PROPERTIES OF Ti-13V-11Cr-3Al SHEET AGED 72 HOURS AT 900 F[1]

Producers of Ti-13V-11Cr-3Al alloy recommended interstage annealing of sheet parts where deformation is severe. A 1350 to 1400 F treatment is recommended. Stress relief of parts formed from solution-treated stock may be accomplished during subsequent aging at 900 F. If aging is not planned, 15 minutes at 1000 F stress-relief annealing is recommended.[5]

1-6.6.3.2 Annealing

Annealing for Ti-13V-11Cr-3Al alloy is the same as solution treating.

1-6.6.3.3 Strengthening Heat Treatments

High strengths can be achieved in the Ti-13V-11Cr-3Al alloy through a duplex heat-treatment process. In general, solution annealing above 1400 F followed by water quenching or air cooling (the beta alloy is not very sensitive to cooling rate because of the high beta-stabilizer content) prepares the material for subsequent aging. Aging treatments may vary widely, but usually are carried out within an 800 to 1000 F temperature range.

1-6.6.3.3.1 Hardenability

Very thick sections of Ti-13V-11Cr-3Al alloy (as in forgings) may be hardened by aging treatments to high strength levels from the solution-annealed condition.

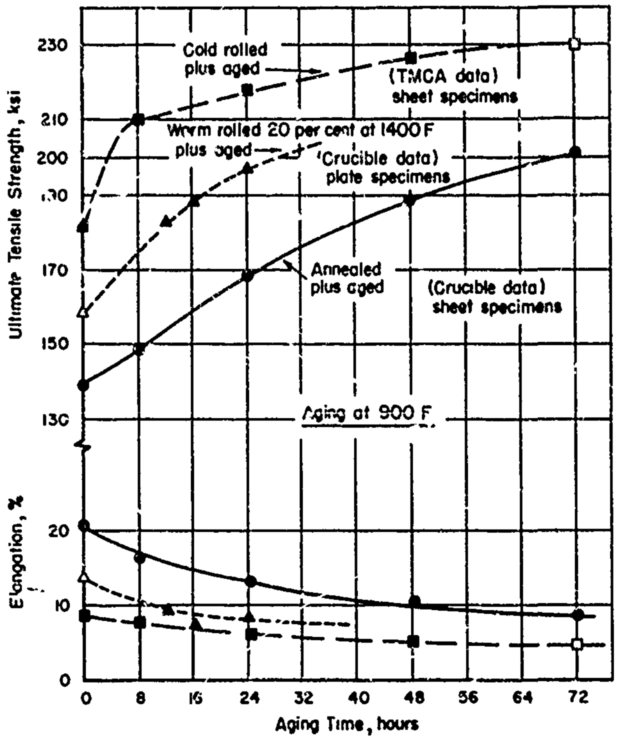

FIGURE 1-6.6.2-3. EFFECT OF WARM AND COLD ROLLING ON THE LONGITUDINAL AGED TENSILE PROPERTIES OF THE Ti-13V-11Cr-3Al ALLOY[1]

1-6.6.3.3.2 Solution Annealing

As might be expected, solution temperature variables affect the subsequent aging response. Long periods at high temperatures result in subsequent undesirable aged properties (low ductility), possibly from grain growth and associated breakdown of favorable nucleation-site distribution. The grain-growth rates of Ti-13V-11Cr-3Al alloy at four temperatures are depicted in Figure 1-6.6.3.3.2-1.[1,6] The effect of solution temperature on the aging response of the alloy as it effects hardness is shown in Figure 1-6.6.3.3.2-2.[1] Within the solution-temperature range (1300 to 1900 F), there is little change in aging response. Data are available that indicate the insensitivity to cooling rate from solution temperature on the subsequent aged tensile properties. Water quenching from the solution-heat-treatment temperatures does not offer a significant advantage over air cooling, except where it might aid in removing heat from thick sections.

1-6.6.3.3.3 Aging Heat Treatments

The advantage of increased strength is gained by heat treatments that modify the metastable beta structure to beta plus the decomposition products.

For all practical purposes, the decomposition of the metastable beta is unattainable below about 600 F. Normally, the aging of the solution-treated

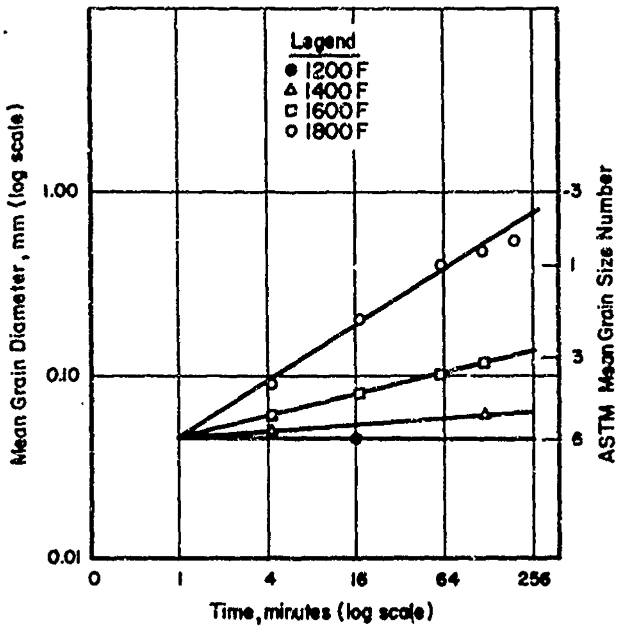

FIGURE 1-6.6.3.3.2-1. GRAIN SIZE OF Ti-13V-11Cr-3Al ALLOY VERSUS TIME AT INDICATED TEMPERATURE[1]

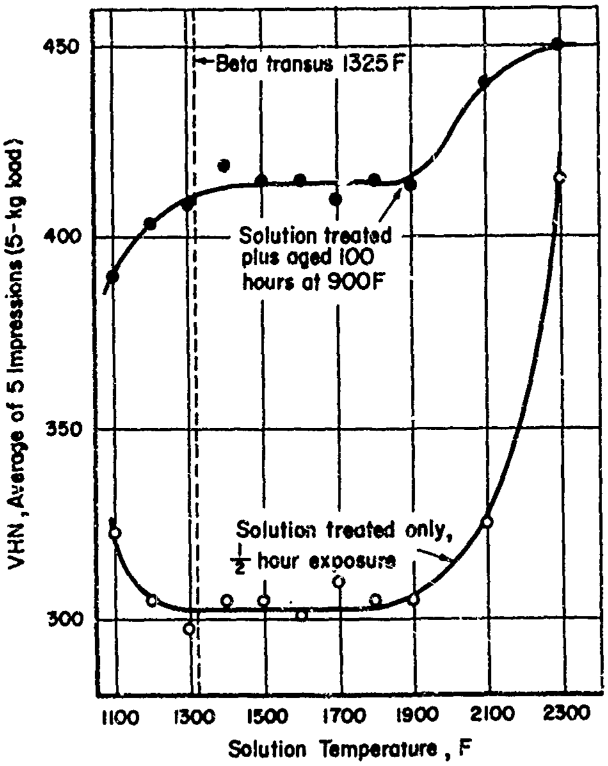

FIGURE 1-6.6.3.3.2-2. EFFECT OF SOLUTION TEMPERATURE ON THE ANNEALED AND ANNEALED PLUS 900 F AGED HARDNESS OF Ti-13V-11Cr-3Al ALLOY[1]

and cooled alloy is accomplished by long-time exposure (20 to 100 hours) at temperatures between 800 and 950 F. These conditions are readily understood from the TTT data illustrated in Figure 1-6.6.1-3. The effects of aging times and temperatures on tensile properties are shown in Figure 1-6.6.3.3.3-1[1], which summarizes the data obtained from Titanium Metals Corporation of America, Martin Aircraft Company, and Crucible Steel Company. These data are for longitudinal sheet specimens, which differ only slightly from data obtained with transverse specimens. The data show that peak aging response is obtainable at about 900 F. Based on these data, overaging does not occur in times up to 100 hours using the 900 or 1000 F aging temperatures. Presumably, overaging would occur with longer holding times at these temperatures. Single aging at 600, 700, 800, 900, and 1000 F for times up to 500 hours did not result in overaging in one group of tests.[7]

As mentioned previously, aged-strength and ductility combinations and rate of aging are dependent upon the processing history of the metal being heat treated. It has been determined that optimum aged properties are obtainable when the prior history of the metal is such as to create favorable nucleation distribution. This in general implies some residual strain energy to promote dispersed nucleation. Cold-worked plus annealed material has different aging characteristics than fully annealed metal. Generally, the effects of residual strain energy on the aging response of the alloy are twofold: (1) acceleration of the aging reaction and (2) somewhat better ductility for some strength levels.

1-6.6.4 Stability

Since the Ti-13V-11Cr-3Al alloy in the annealed condition is subject to precipitation reactions, as illustrated in Figure 1-6.6.1-3, the thermal stability of this alloy in this condition is definitely limited to those times and temperatures that do not cause the metallurgical reactions. As stabilized by an aging treatment, the Ti-13V-11Cr-3Al alloy is much more thermally stable since the metastable beta has already been decomposed to equilibrium products. Chemically, the beta alloy might be expected to be very inactive because of its high alloy content. However, it reacts to interstitial contaminants in much the same way and to about the same extent as other titanium alloys and has been shown to be fairly susceptible to hot-salt stress corrosion.

1-6.6.4.1 Thermal Stability

The ability of the solution-annealed beta alloy to maintain mechanical properties at elevated temperature is limited to fairly short exposure time at temperatures up to about 600 F. The change in properties of solution-annealed metal as well as the added effect of cold work on the thermal-exposure stability of Ti-13V-11Cr-3Al is shown in Figure 1-6.6.4.1-1.[1] The effect of an added variable, stress, is shown below and in Table 1-6.6.4.1-1.[1]

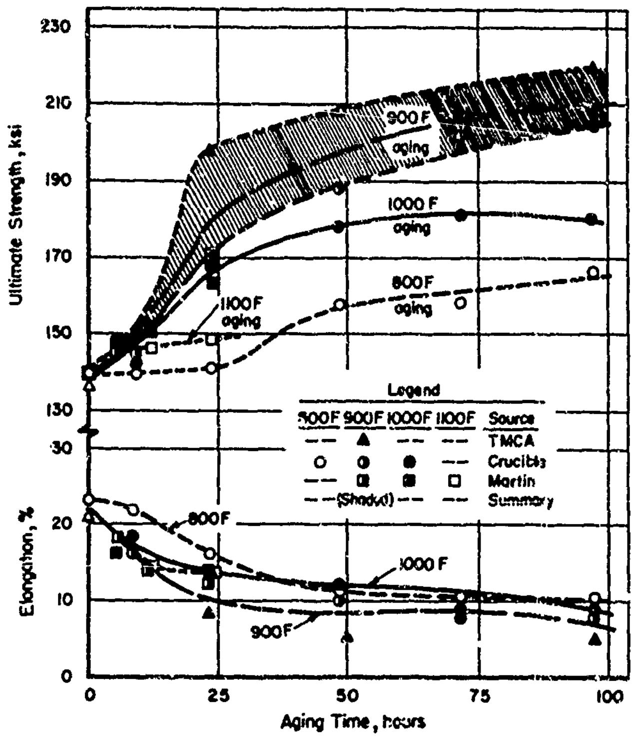

FIGURE 1-6.6.3.3.3-1. EFFECT OF AGING TIME ON THE LONGITUDINAL SHEET TENSILE PROPERTIES OF THE Ti-13V-11Cr-3Al ALLOY[1]

Exposure Conditions	UTS, ksi	0.2% Offset YS, ksi	El, %	RA, %
500 hr at 600 F, no stress	202	193	6.0	16
500 hr at 600 F, 30 ksi	201	195	1.3	--

The thermal stability of aged metal is better than solution-annealed metal, as would be expected. Tensile data before and after creep exposure are given in Tables 1-6.6.4.1-2[1] and 1-6.6.4.1-3[1] which verify this. It is generally conceded however, that even for aged material, the temperature limit for thermal stability in Ti-13V-11Cr-3Al is 575-600 F for long-time exposure.

1-6.6.4.2 Chemical Stability

The reactivity of the all-beta alloy in chemical environment is fairly typical of all titanium alloys. Reactivity increases with increasing temperature. The Ti-13V-11Cr-3Al does not appear to discolor and scale up as badly as some other titanium alloys at temperatures as low as at 500 to 600 F; however, little difference in discoloration and scaling is noted at higher temperatures. An indication of the depth of scale buildup at solution annealing temperatures is given by the data in Table 1-6.6.4.2-1.[1]

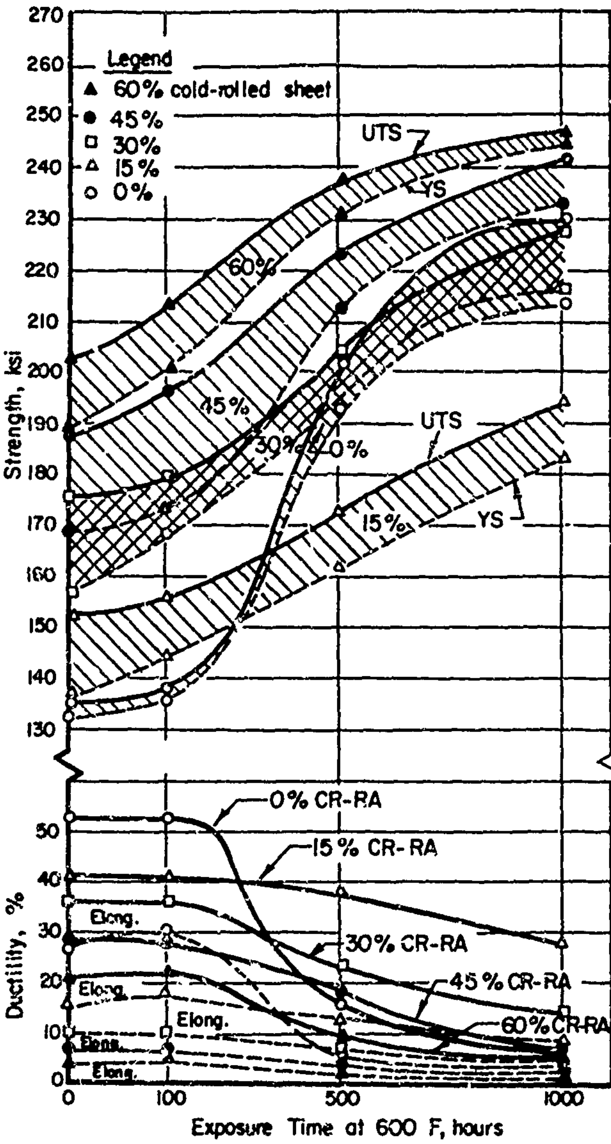

FIGURE 1-6.6.4.1-1. EFFECT OF 600 F THERMAL EXPOSURE ON THE TENSILE PROPERTIES OF COLD-ROLLED Ti-13V-11Cr-3Al ALLOY[1]

Limited test data are available showing the hot-salt-stress corrosion susceptibility of Ti-13V-11Cr-3Al alloy. The NASA experiments indicated that most salt-exposed material in the aged condition will crack in 550 F, 100-ksi exposure during a 4000- to 6000-hour run.[8] There were indications in the same program that Ti-13V-11Cr-3Al alloy was not quite as susceptible to salt corrosion as Ti-6Al-4V or Ti-8Al-1Mo-1V alloys.

More recently, in tests conducted at the Lockheed Aircraft Company, California, 500 F salt exposure tests indicated a pronounced stress corrosion susceptibility of both annealed and aged Ti-13V-11Cr-3Al alloy when exposed in tests simulating various fastening techniques (e.g.,

TABLE 1-6.6.4.1-1. CREEP AND CREEP-STABILITY DATA FOR ANNEALED Ti-13V-11Cr-3Al SHEET(1)

Creep-Exposure Conditions			Total Plastic Deformation, %	Room-Temperature Tensile Properties		
Temperature, F	Stress, ksi	Test Duration, hours		Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, %
Not exposed	--	--	--	129	127	25
300	60	500	-0.3(b)	130	130	24
Not exposed	--	--	--	128	126	24
300	60	500	-0.2(b)	128	128	22
Not exposed	--	--	--	142	141	23
400	90	474	0.15	(a)	(a)	20
400	100	496	0.19	(a)	(a)	23
Not exposed	--	--	--	129	127	21
500	40	500	-0.2(b)	130	130	25
Not exposed	--	--	--	127	126	21
500	40	500	-0.4(b)	132	131	23
500	80	547	0.02	(a)	(a)	18
500	90	305	0.15	(a)	(a)	20
Not exposed	--	--	--	128	126	25
600	30	500	0.2	213	210	1.2
Not exposed	--	--	--	128	125	22
600	30	500	0.8	188	180	1.5

(a) Strengths not reported.
(b) Negative strain measurements.

TABLE 1-6.6.4.1-2. CREEP AND CREEP-STABILITY DATA FOR AGED Ti-13V-11Cr-3Al SHEET(1)

(Aging Heat Treatments Not Described)

Creep-Exposure Conditions			Total Plastic Deformation, %	Room-Temperature Tensile Properties		
Temperature, F	Stress, ksi	Test Duration, hours		Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, %
No exposure	--	--	--	200	180	5.0
500	105	1502	0.05	197	180	6.5
500	105	1502	0.14	171	165	5.0
No exposure	--	--	--	190	170	6.0
575	65	1503	0.07	182	169	6.0
575	100	1435	0.10	211	196	OGM(a)
575	100	1507	0.10	210	188	6.5
No exposure	--	--	--	200	180	5.0
600	95	1502	0.11	220	184	2.0
600	100	712	0.16	215	192	6.5
No exposure	--	--	--	189	174	10.5
625	65	100	0.00	192	176	8.5
No exposure	--	--	--	200	180	5.0
800	80	10	0.15	202	185	3.0
800	100	10	0.24	197	186	--
No exposure	--	--	--	140	135	22.0
800	80	10	0.12	147	146	15.0
800	100	10	0.58	151	151	10.0

(a) OGM = Broke on gage mark.

TABLE 1-6.6.4.1-3. CREEP AND CREEP-STABILITY DATA FOR AGED Ti-13V-11Cr-3Al SHEET (0.022-INCH)[1]

Solution treated 1/2 hour at 1400 F, AC, aged 112 hours at 900 F, AC.

RT Tensile Properties Prior to Creep Exposure

Ultimate, ksi	Yield, ksi	Elongation, %	Reduction in Area, %
189.9	167.8	15.0	37.0
186.0	164.6	13.3	38.4
191.0	170.6	11.7	37.2

Creep Stress, ksi	Duration of Test, hr	Plastic Creep, %	RT Properties Subsequent to Creep Exposure: Ultimate Strength, ksi	0.2% Yield Strength, ksi	Elongation, %	RA, %
40.0	286	0.707	205.5	189.0	10.0	27.6
40.0	286	0.705	208.4	192.8	10.0	29.6
38.7	286	0.626	205.2	187.7	10.0	29.0
38.7	286	0.633	202.3	185.3	10.0	35.5
41.3	286	0.830				
41.3	598	1.137	193.9	187.2	Nil	3.0
40.6	286	0.791				
40.6	598	1.109	209.7	195.7	3.3	6.5
40.0	286	0.785				
40.0	598	1.112	210.3	194.7	3.3	6.5
40.0	286	0.802				
40.0	598	1.100	204.1	189.0	1.7	3.0
31.4	286	0.393	204.4	184.1	10.0	38.2
30.0	286	0.530	204.6	(a)	11.7	28.6
29.6	286	0.707	206.9	(a)	10.0	25.7
30.0	286	0.491				
30.0	598	0.620	203.2	182.9	5.0	8.3
29.6	286	0.517				
29.6	598	0.577	205.6	187.7	6.7	13.9

(a) Retested without extensometer, after grip failure.

rivet, screw, spot, and fusion welds). Some susceptibility also was indicated on material worked by bending. Thus, while stress levels that promote stress corrosion are undefined in these tests, it is apparent that operations resulting in high residual stresses result in the salt-cracking phenomenon at 500 F in times less than 2000 hours and in most fastener applications in times less than 100 hours.

While the laboratory experience indicates the hot-salt stress corrosion susceptibility of the all-beta alloy, it should be noted that intentional salting may be much more damaging than service environment. The all-beta alloy is in use on supersonic aircraft, and while experience is probably short and is not subject to public inspection, it is noteworthy that material changes in such supersonic aircraft have not been ordered.

1.6-7 REFERENCES

(1) Wood, R. A. and Ogden, H. R., "The All-Beta Titanium Alloy (Ti-13V-11Cr-3Al)", DMIC Report 110, Battelle Memorial Institute, (April, 1959).

TABLE 1-6.6.4.2-1. HARDNESS AND DEPTH OF SCALE MEASUREMENTS ON Ti-13V-11Cr-3Al ALLOY AFTER SOLUTION-ANNEALING TREATMENTS[1]

Solution Heat Treatment(a)	Average Vickers Hardness(b), 20-kg load	Maximum Scale Depth(c), inch
1 hr 1600 F, AC	306	0.0013
2 hr 1600 F, AC	318	0.0022
4 hr 1600 F, AC	349	0.0033
1 hr 1700 F, AC	304	0.0024
2 hr 1700 F, AC	347	0.0017
4 hr 1700 F, AC	296	0.0038
1 hr 1800 F, AC	366	0.0025
1 hr 1800 F, FC	344	0.0047

(a) AC = air cooled, FC = furnace cooled.
(b) Surface or cross section test direction not reported.
(c) Determined by microscopic examination of cross section.

(2) Godfrey, L. and Makowski, R., "Research and Development of Titanium Rocket Motor Case", WAL 766.2/-14, Final Report on Contract DA-19-020-ORD-5230, Volume I, Pratt & Whitney Aircraft Company (October, 1963).

(3) Mitchell, D. R., "The Welding of Ti-13V-11Cr-3Al", TMCA Report (December, 1960).

(4) Hauser, H. A. and Helfrich, W. E., "Research and Development of Titanium Rocket Motor Case", WAL 766.2/1-10, Progress Report No. 11 on Contract DA.19-020-ORD-5230, Pratt & Whitney Aircraft Company (January 1 to March 31, 1963).

(5) "Properties of Ti-13V-11Cr-3Al, The Meta-Stable Beta Titanium Alloy Grade", Titanium Engineering Bulletin No. 9, TMCA (no date).

(6) Crossley, F. A., "The Effect of Addition Elements on the Rate of Beta Grain Growth in Alpha-Beta and Beta-Titanium Alloys", ASD-TDR-62-520 (November, 1962).

(7) Moreen, R. I., Federico, A.M., et al., "Evaluation of Rem-Cru B-120 VCA", North American Aviation, Inc., Columbus, Ohio (January, 1959).

(8) Braski, D. N. and Heimerl, G. J., "The Relative Susceptibility of Four Commercial Titanium Alloys to Salt Stress Corrosion at 550 F", NASA TN D-2011 (December, 1963).

1-7 Titanium Alloy Ti-4Al-3Mo-1V

1-7.0 GENERAL REMARKS

The Ti-4Al-3Mo-1V alloy was initially developed to meet the needs for a highly formable material which could be subsequently aged to very high strength. Extensive testing of this material during the Department of Defense Sheet Rolling Program indicated a highly desirable combination of properties. More recently, testing of materials for SST candidacy showed that the Ti-4Al-3Mo-1V alloy is highly resistant to aqueous stress corrosion. The material is essentially limited to flat-rolled products.

1-7.1 COMMERCIAL DESIGNATIONS

Designation	Producer	Forms Available[a]
C-115AMoV	Crucible Steel Company	S,s,P
RMI-4Al-3Mo-1V	Reactive Metals, Incorporated	S,s,P
Ti-4Al-3Mo-1V	Titanium Metals Corporation	S,s,P

(a) S = sheet, s = strip, P = plate.

1-7.2 ALTERNATE DESIGNATIONS (COMMON NAMES)

Ti-4-3-1, 4-3-1, or 431 alpha-beta alloy.

1-7.3 ALLOY TYPE

Alpha-beta (rich-beta content).

1-7.4 COMPOSITION, RANGE OR MAXIMUMS, %

Major Elements		Interstitial Elements	
Aluminum	3.75-4.75	Carbon	0.08 max
Molybdenum	2.5-3.5	Nitrogen	0.05 max
Vanadium	0.5-1.5	Oxygen	--
Iron	0.25 max	Hydrogen	0.015 max

1-7.5 SPECIFICATIONS

AMS 4912
AMS 4913
MIL-T-9046F
MIL-T-8084 (ASG)
MIL-T-14558

1-7.6 ALLOY DESCRIPTION AND METALLURGY

1-7.6.1 Composition and Structure

The Ti-4Al-3Mo-1V alloy is an alpha-beta alloy in which only a moderate amount of alpha-stabilizer content, 4 percent aluminum, is balanced against the strong beta-stabilizing characteristics of the 3 percent molybdenum plus 1 percent vanadium content. One result of this combination of alloying additions is that relatively large amounts of the beta phase can be stabilized to room temperature during solution treatment. The usual structure of the solution-treated condition is therefore a mixed alpha-beta structure which is fine-grained and composed of primary equiaxed alpha grains in a beta-phase matrix. This structure is a relatively low-strength, high-ductility structure which can be subsequently age hardened. Aging consists of reheating to moderately elevated temperatures. It is believed that the aging reaction consists of decomposition of the beta phase, which transforms to the low-temperature equilibrium alpha phase plus intermediate phases during aging. The richness of the beta phase affords a large aging response; that is, the alloy can be aged to a very high-strength condition. The appearance of the aged structure metallographically is like the solution-heat-treated structure except that the beta matrix is dark staining after the aging treatment.

1-7.6.2 Deformation Practice and Effects[1]

The Ti-4Al-3Mo-1V composition represents a type of titanium, alpha-beta alloy uncommon to current commercial grades with regard to formability. It is essentially a flat-rolled product alloy, and therefore sheet-forming operations are emphasized in this section. The Ti-4Al-3Mo-1V alloy is unique inasmuch as formability limits approach those for some unalloyed grades and yet the material can subsequently be strengthened by heat treatment. It is unique in part because of the large spread between yield and ultimate strength in the solution-treated condition, which permits extensive deformation without appreciable thinning or rupture. The alloy can be formed in either the annealed, the solution-treated, or in the solution-treated plus aged condition. Also, the alloy can be formed from room temperature to fairly high temperatures, but, of course, the original sheet condition, the severity of the forming operation, and the final properties desired, dictate the selection of forming temperatures.

Solution-heat-treated Ti-4Al-3Mo-1V alloy has a low yield strength (as low as 90 ksi) and excellent ductility at room temperature. These properties do not change appreciably until temperature exceeds 1000 F. Thus, hot forming of the solution-treated material offers little or no improvement over cold forming until forming temperatures exceed 1000 F. Hot stretching and hot, drop-hammer forming of solution-treated sheet above 1000 F may have certain advantages over cold forming. The use of temperatures higher than the preferred aging temperature results in a

gradual deterioration of subsequent aged properties. If very high forming temperatures are required to make a part, there is no advantage in using solution-heat-treated material. Annealed, flat-rolled product should be used in such cases. After forming, the material can then be put into the solution-treated plus aged condition.

Forming operations in the solution-treated condition such as brake-press bending, stretching of skins, and joggling can be done at room temperature. More severely formed parts, such as complex curvatures or stretch and shrink flanges, generally require a sequence of cold forming followed by hot sizing in matched dies. Final hot sizing at elevated temperatures eliminates springback and buckled flanges. Use of a hot-sizing operation results in final parts of close dimensional tolerance.

Sheet material in the solution-treated condition is guaranteed to bend 105 degrees without cracking around a radius of:

3.5 x sheet thickness for gages 0.070 inch and less.
4.0 x sheet thickness for gages 0.070 inch to 0.187 inch.

Parts involving long bends can be successfully formed on production shop equipment by employing a die having a radius approximately one sheet thickness greater than these guaranteed bend radii.

A loss of 15 to 25 degrees in the included bend angle must be expected because of springback in forming at room temperature. This will be true of flange angles formed by brake press, rubber press, or drop hammer. Springback may be compensated for by overforming, or may be eliminated by subsequent hot sizing in matched dies.

Ti-4Al-3Mo-1V sheet in the solution-treated condition may be stretch formed and stretch wrapped at room temperature. Full-range stress-strain curves for solution-treated sheet are shown in Figure 1-7.6.2-1. Over one half of the tensile elongation is distributed uniformly over the length of a unidirectional-stretched section. Wrap forming and stretch wipe forming of angled sections at room temperature followed by hot sizing to eliminate springback and twist is a recommended procedure

Stretch and shrink flanged parts having large radii of curvature and short flange heights may be formed at room temperature without buckling. Springback must be allowed for in the die design. More severe curvatures and greater flange heights are obtained by cold rubber forming followed by hot sizing to eliminate springback and remove buckles. The maximum buckle that can be removed in a hot-sizing operation determines the design limit of flange height or curvature radius. Beyond a certain severity, buckles cannot be removed in hot sizing without exceeding the allowable temperature limitations imposed by aging response.

Cold forming of parts to approximate dimensions on the drop hammer can be followed by a hot sizing operation to attain final part dimensions. If the complexity of the part makes hot sizing impractical, higher blank temperatures must be used to make the material flow under the hammer.

Acceptable joggles can be produced at room temperature. Joggles having a length-to-depth ratio as severe as 2:1 at depths as high as six times sheet thickness have been produced cold.

Conduction heating and triple-action ram coin dimpling at ram loads in the range of 5,000 pounds produce satisfactory dimples for rivets. Sheet temperatures should attain 1000 to 1100 F. Care should be taken to avoid surface overheating or oxidation during all hot forming operations.

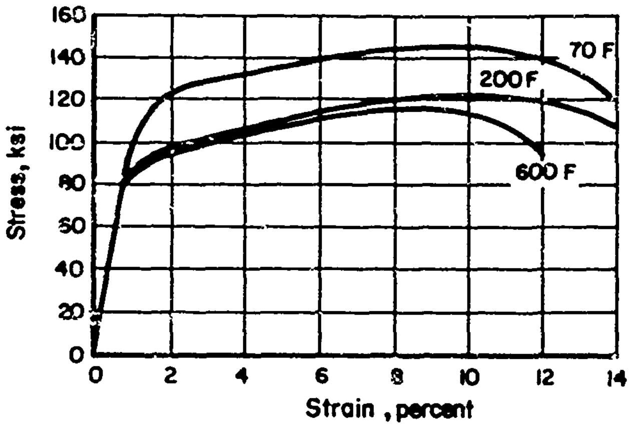

FIGURE 1-7.6.2-1. THE EFFECT OF TESTING TEMPERATURE ON STRESS-STRAIN CURVES OF SOLUTION-TREATED Ti-4Al-3Mo-1V SHEET[1]

When hot forming at temperatures above 1150 F is required to improve bendability or general formability, material in the annealed condition should be used. Complex parts can be formed by heating annealed blanks to temperatures of 1100 to 1400 F -- the best approach is that of heating the work material, staging of the part through several dies, with interstage annealing.

Above 1000 F, material in the annealed condition loses strength and gains ductility very rapidly. Bend ductility improves to the point where a 90-degree 1T radius bend may be obtained at 1200 F and higher.

Full-range stress-strain curves from room temperature to 1000 F for material in the annealed condition are shown in Figure 1-7.6.2-2.

There is no detrimental effect, other than oxidation, from heating to temperatures up to 1500 F. Oxidation becomes significant above 1100 F.

When annealed material is used for forming, the formed part must be solution treated and aged to attain high strength after the forming operation. During the water quench from the solution temperature, distortion of the part may require a final sizing operation. Drop-hammered parts may be restruck following solution treatment to obtain final dimensions.

Sheet, fully or partially aged, is recommended as starting material for fabrication of single-contour skins requiring a small amount of deformation by stretching, or double-contour-skin sections that are to be creep formed. The use of aged sheet eliminates furnace time normally encountered in the age cycle.

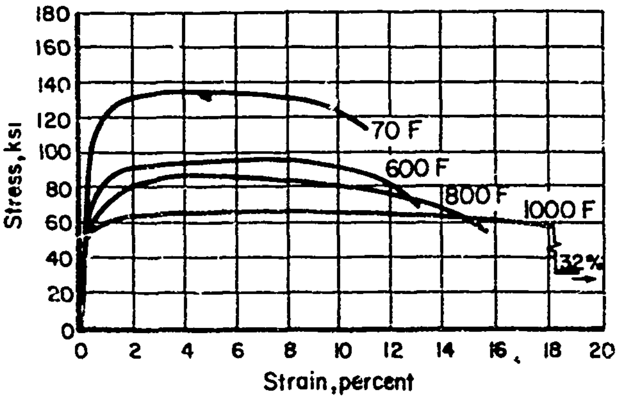

FIGURE 1-7.6.2-2. THE EFFECT OF TESTING TEMPERATURE ON THE STRESS-STRAIN CURVES OF ANNEALED Ti-4Al-3Mo-1V[1]

Small amounts of tensile strain in aged material result in a significant loss in the compression yield strength. This loss in compression yield strength may be restored by a short stress-relief treatment. Thirty minutes at 1000 F will not impair the aged tensile properties and will eliminate Bauschinger effects.

Creep forming of STA material, to be successful, should be done in the range 850 to 1000 F. Care must be taken not to overage during the creep-forming operation. Allowable times to prevent overaging vary from 2 hours at 900 F to 1 hour at 1000 F.

The term "Hot Sizing" refers to a widely accepted practice in the airframe industry; that is, employment of a high-temperature deformation mechanism whereby rough-shaped parts are forced to assume a specified geometry. Hot sizing is generally accomplished by restraining the part in matched dies of the required part shape and holding the dies and part at a sufficiently high temperature or by using hot-sizing presses having heated platens. The minimum hot-sizing temperature is that which is required to dissipate residual elastic stresses and cause the material to strain slowly by creep deformation. Maximum temperatures, when solution-treated material is being sized, are those that do not cause excessive overaging or loss in subsequent aging response. For Ti-4Al-3Mo-1V solution-treated sheet, the allowable temperature range for hot sizing is 925 to 1125 F.

The degree of sizing obtained is a function of time of exposure, as well as of temperature. When hot presses are available, production considerations generally limit the allowable exposure time to 10 to 20 minutes. Using this optimum production exposure time, Ti-4Al-3Mo-1V requires a sizing temperature between 1050 F and 1100 F. When parts are restrained in dies and heated in conventional furnaces, times necessarily must be longer. In such cases, the temperature of exposure should not exceed 1050 F.

Aging can be accomplished concurrently with the hot-sizing operation. This procedure is applicable when the aging temperature, 925 F, is sufficient to hot size the part. Aging time in the hot-sizing operation is not critical in the range from 6 to 12 hours.

Deformation and high-temperature heating during fabrication may change both the solution-treated and final aged properties. Straining and overheating can both have deleterious effects upon this type of alloy if improperly controlled. Proper attention to fabrication deformation and temperature as well as aging and stress-relief cycles will result in finished parts having excellent strength and ductility.

When solution-treated sheet is strained in tension, the solution-treated tensile properties change because of a strain-hardening effect. Figure 1-7.6.2-3 illustrates the increase in yield strength and loss in ductility due to such deformation.

Ti-4Al-3Mo-1V is free from any serious detrimental straining effect upon aged tensile properties. Solution-treated sheet, deformed in tension and subsequently aged, retains almost all its full-aged capabilities, as shown in Figure 1-7.6.2-4. Minimum guaranteed aged properties are retained even with large prestrains.

The compression properties of aged Ti-4Al-3Mo-1V sheet are slightly affected by prior

deformation in the solution-treated condition, as shown in Figure 1-7.6.2-5.

Solution-treated Ti-4Al-3Mo-1V sheet begins to age at temperatures above 600 F. Figure 1-9.6.2-6 illustrates that short times at temperatures above 600 F result in an increase in strength and a decrease in ductility due to aging. At temperatures approaching normal aging (925 F), strength increases rapidly and ductility decreases. Because of this effect, hot forming material in the solution-treated condition shows little or no advantage over cold forming until temperatures exceeding 1000 F are employed.

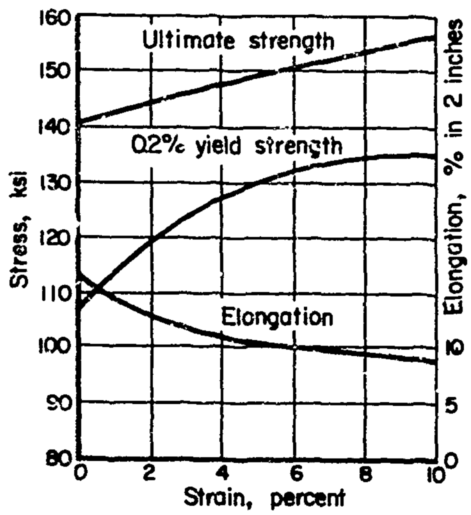

FIGURE 1-7.6.2-3. EFFECT OF TENSILE STRAIN IN SOLUTION-TREATED CONDITION ON THE SOLUTION-TREATED TENSILE PROPERTIES OF Ti-4Al-3Mo-1V SHEET(1)

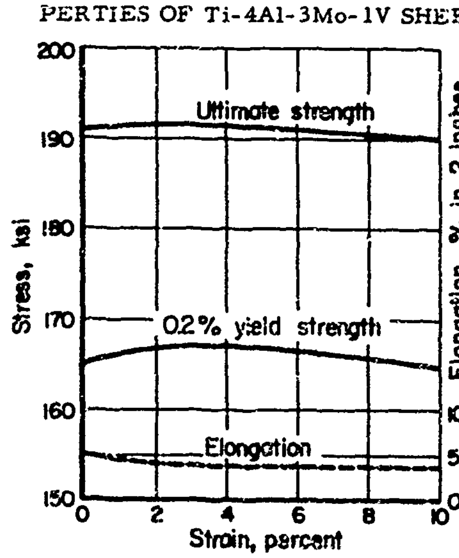

FIGURE 1-7.6.2-4. EFFECT OF TENSILE STRAIN IN THE SOLUTION-TREATED CONDITION ON FINAL AGED TENSILE PROPERTIES(1)

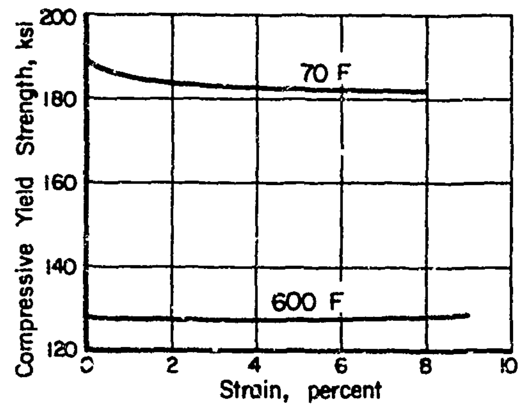

FIGURE 1-7.6.2-5. EFFECT OF TENSILE STRAIN IN SOLUTION-TREATED CONDITION ON FINAL AGED COMPRESSION PROPERTIES(1)

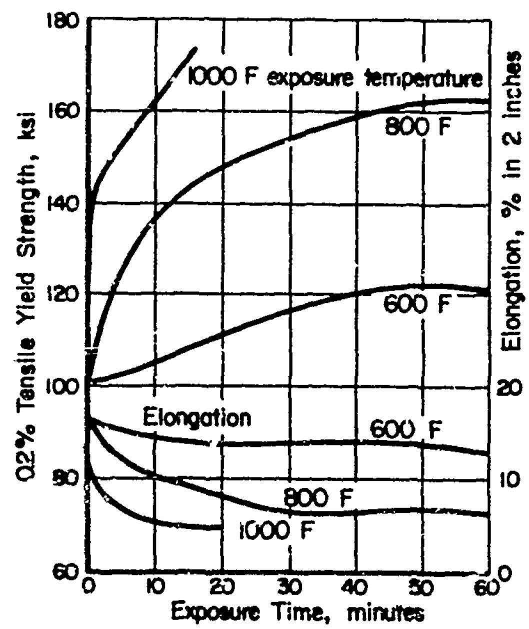

FIGURE 1-7.6.2-6. EFFECT ON EXPOSURE AT TEMPERATURES UP TO 1000 F ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF SOLUTION-TREATED Ti-4Al-3Mo-1V(1)

Hot working or hot sizing at temperatures up to 1000 F has no detrimental effect on the aged tensile properties of Ti-4Al-3Mo-1V. Exposure times of up to 1 hour at 1000 F do not decrease the aged tensile properties. This is true whether the material is aged prior to exposure or subsequent to the hot sizing or working operation. For mild hot-sizing operations, aging may be accomplished

simultaneously by restraining the part during the 12-hour age at 925 F.

However, most hot-sizing and some dynamic-forming operations may require use of temperatures from 1000 to 1200 F. Times at these temperatures will generally be from 10 to 20 minutes.

When exposure temperature exceeds 1050 F, a drop in the final aged properties is encountered, as shown in Figure 1-7.6.2-7.

Losses in both tension and compression strength of material in the aged condition become prohibitive after exposure to temperatures exceeding 1100 to 1150 F. The sequence of forming, aging, and hot sizing is sometimes important. The loss in compression yield strength due to over-heating has been shown to be less when aging follows hot sizing than when hot sizing follows aging. There is little difference in final aged tensile properties regardless of the sequence of contouring and aging operations.

Figure 1-7.6.2-8 illustrates that approximately 90 percent of the original compression yield strength is retained after a representative fabrication sequence of 10 percent strain and 1100 F exposure for 15 minutes. The use of lower exposure temperatures, 1000 F, results in greater retention of compression strength.

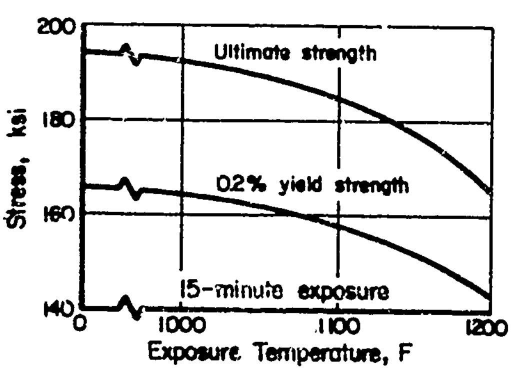

FIGURE 1-7.6.2-7. EFFECT OF EXPOSURE TO TEMPERATURE ABOVE THE AGING TEMPERATURES ON FINAL-AGED TENSILE PROPERTIES[1]

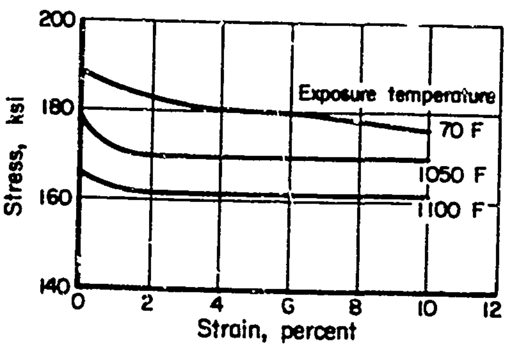

FIGURE 1-7.6.2-8 EFFECT OF DEFORMATION AND EXPOSURE TEMPERATURE ON THE COMPRESSION YIELD STRENGTH OF AGED Ti-4Al-3Mo-1V SHEET[1]

In summarizing, the Ti-4al-3Mo-1V alloy may be formed extensively without serious degradation of properties, provided proper forming techniques are used on material in selected conditions. A summary guide to condition selection and some advantages and disadvantages of these conditions is given below.[1]

Solution Treated (ST)

- Best cold formability
- Hot contouring can be used in conjunction with cold forming to give final part dimensions
- Can be aged directly to high strength condition

Aged (STA)

- High strength and limited ductility for forming
- Applicable where limited contouring, stretching, or bending is needed
- Requires no additional aging to obtain a high strength condition

Annealed (Ann)

- Where hot forming above 1100 F is required to obtain parts of final dimension
- Elongation and bend ductility is excellent above 1000 F
- Final part must be solution treated and aged to obtain a high strength condition.

1-7.6.3 Heat-Treatment Practice and Effect

1-7.6.3.0 General Remarks

The Ti-4Al-3Mo-1V alloy has been a popular material choice where combinations of excellent formability and high strength are desirable. High strength is associated with material in the aged condition, which of course must be imposed upon material in the solution-heat-treated condition. Excellent formability also is a characteristic of this material in the annealed condition, although as annealed the material is not a high-strength alloy. At the lower strength levels characteristic of either annealed material or material in the solution treated and overaged condition, the Ti-4Al-3Mo-1V alloy has excellent fracture toughness. Beta processing or heat treatment followed by solution treating and overaging imparts additional toughness to this alloy grade with little sacrifice in the strength level achievable.

1-7.6.3.1 Stress-Relief Annealing

Stress-relief annealing treatments for the Ti-4Al-3Mo-1V alloy are intended to relieve the residual stresses and restore yield strength without otherwise affecting mechanical properties. Stress-relieving temperatures in the 900 to 1100 F range are compatible with aging and hot-sizing temperatures. Exposure time of about 1 hour is sufficient for many stress-relieving operations at the higher temperatures (1000 to 1100 F). Hot-sizing, aging, and stress-relieving operations can be combined. Care should be taken at the highest stress-relieving temperatures to minimize oxidation, although oxidation is not much of a problem below 1100 F.

1-7.6.3.2 Annealing

The annealing heat treatment for the Ti-4Al-3Mo-1V alloy consists of exposure at about 1225 F for 4 hours, followed by furnace cooling to 1050 F, then air cooling to room temperature. The annealing treatment is designed to yield a mixed alpha-beta structure that is ductile and stable. Sheet material can be supplied in the annealed condition from the producers when hot-forming operations above about 1150 F are planned. For difficult-to-form parts, interstage annealing may be required. Whenever interstage annealing may occur in the part-making sequence and whenever the ultimate part is required to be finished in the high-strength condition, solution heat treatment is required between interstage annealing and a final aging treatment.

Duplex annealing also has been developed for the Ti-4Al-3Mo-1V alloy. Duplex annealing consists of annealing the material first at a high temperature such as 1725 F, then air cooling to room temperature, followed by reannealing at a stabilization temperature such as 1150 F (terminated by air cooling). Thirty-minute holding time at the high temperature followed by an 8-hour exposure at the stabilization temperature has been found to yield good toughness and formability characteristics to sheet material. Strength is, of course, lower than in solution-heat-treated and aged material, but toughness is much higher, as shown later.

1-7.6.3.3 Strengthening Heat Treatments

The Ti-4Al-3Mo-1V alloy may be heat treated to a wide range of uniaxial tensile strengths (~150 to 200-ksi US) by selecting different solution-heat-treatment and aging exposures. Ductility and toughness values generally decrease with increasing heat-treatment choice, based on the combinations of strength and ductility or toughness desired. While a considerable number of data have been accumulated showing the effects of different solution treating and aging treatments on properties, it should be noted that the titanium producers from time to time introduce changes in their mill-processing procedures. These changes may include such procedures as beta processing. Such changes can eventually lead to new heat-treatment schedules designed to be more compatible with the newer mill products.

1-7.6.3.3.1 Solution Annealing

The Ti-4Al-3Mo-1V alloy may be solution heat treated over a fairly wide range of elevated temperatures to obtain different ratios of alpha and beta phases. The choice of solution temperature dictates both the properties in the quenched material and also the final-aged strengths obtainable.

The spread between yield and ultimate tensile strength can be made to vary markedly by the choice of solution temperature, as shown in Figure 1-7.6.3.3.1-1. Maximum spread between yield and ultimate strength is found after quenching from between about 1550 and 1650 F. Material in the solution-heat-treated condition offers maximum cold formability because of the low yield strength and maximum ductility obtained from this temperature range. The final-aged strength is quite high after solution heat treating in this temperature range, as indicated by the data shown in Figure 1-7.6.3.3.1-2.

The solution-heat-treatment range formerly preferred for the Ti-4Al-3Mo-1V alloy was 1640 to 1650 F. More recently, a higher solution temperature, 1715-1725 F, is preferred for use with a higher aging temperature, which is described in detail in the following aging-heat-treatment section. Holding times at solution temperatures should be from 10 to 30 minutes. Termination of the solution treatment by water quenching is preferred with quench delay times limited to 5 seconds or less to

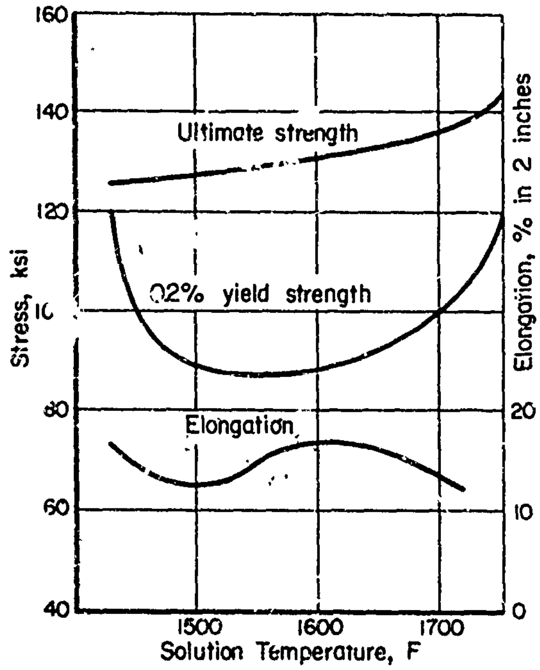

FIGURE 1-7.6.3.3.1-1. TENSILE PROPERTIES OF Ti-4Al-3Mo-1V ALLOY SOLUTION HEAT TREATED AT VARIOUS TEMPERATURES[1]

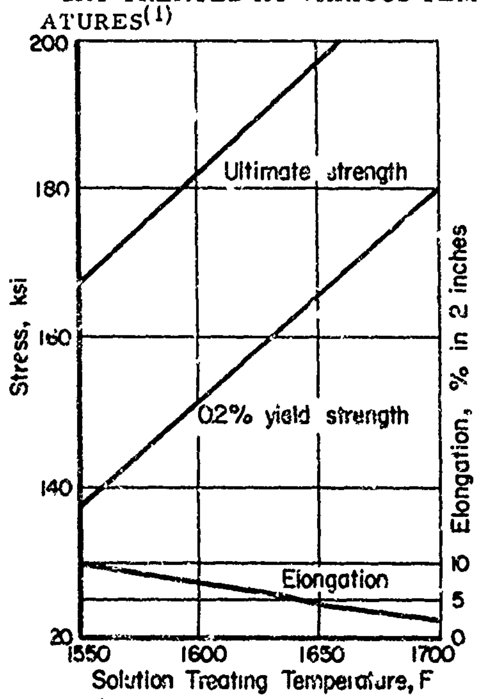

FIGURE 1-7.6.3.3.1-2. EFFECT OF SOLUTION TEMPERATURE ON TENSILE PROPERTIES OF Ti-4Al-3Mo-1V ALLOY AGED AT 925 F AND TESTED AT ROOM TEMPERATURE[1]

retain maximum final aging response. The effect of quench delay time from the solution temperature on final aged tensile strength is shown in Figure 1-7.6.3.3.1-3.

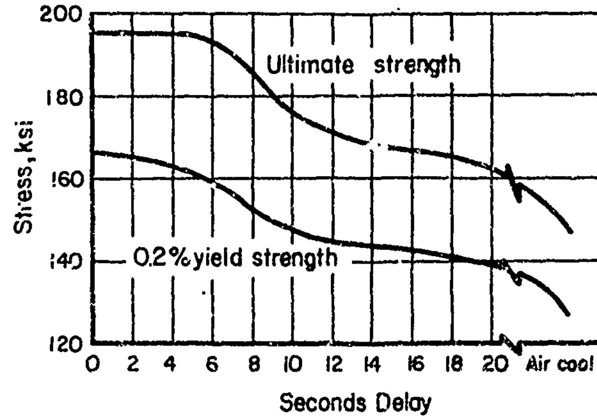

FIGURE 1-7.6.3.3.1-3. EFFECT ON AGED PROPERTIES OF DELAY IN QUENCHING FROM SOLUTION TEMPERATURE (CONVENTIONAL SOLUTION AND AGING HEAT TREATMENTS)[1]

1-7.6.3.3.2 Aging Heat Treatments

Solution-heat-treated Ti-4Al-3Mo-1V alloy begins to age harden at temperatures of 600 F and above. However, the conventional aging-heat-treatment temperature is 925 F. Exposure times at this temperature between 6 and 12 hours result in a very high-strength condition. As the aging temperature is raised above 925 F, the aging reaction. $\beta \rightarrow \beta + \omega \rightarrow \alpha + \beta$, is accelerated so that peak strengths are obtained in shorter times. This effect is shown in Figure 1-7.6.3.3.2-1 for ultimate strength. Figure 1-7.6.3.3.2-2 shows the effect on tensile yield strength and ductility. Also, as shown in Figure 1-7.6.3.3.2-1, temperatures above 1000 F result in overaging in fairly short times. This may be undesirable if a maximum strength condition is desired. On the other hand, overaging heat treatments (8 hours at 1050 to 1150 F) are now becoming popular when used in conjunction with beta processing to achieve maximum fracture-toughness characteristics at the expense of a maximum strength condition.

As mentioned in the preceding section on solution annealing, the overaging heat treatments are usually used on material that has been solution heat treated at a temperature very high in the alpha-plus-beta region (1715-1725 F). Such high-temperature solution-annealing and overaging treatments can be given to material that has been previously beta heat treated or processed. The beta-processing temperature of 1875 F, exposure for 30 minutes followed by air cooling to room temperature, has been used in conjunction with a 1725 F solution temperature and either 1050 F or 1150 F overaging heat treatments. The additional toughness advantage obtained for material thus processed is shown in Figure 1-7.6.3.3.2-3. The notched toughness of material aged to different strength levels using conventional solution and

agii g treatments is shown in Figure 1-7.6.3.3.2-4. Typical tensile properties of conventionally aged Ti-4A.·3Mo-1V alloy at test temperatures to 1000 F are shown in Figure 1-7.6.3.3.2-5.

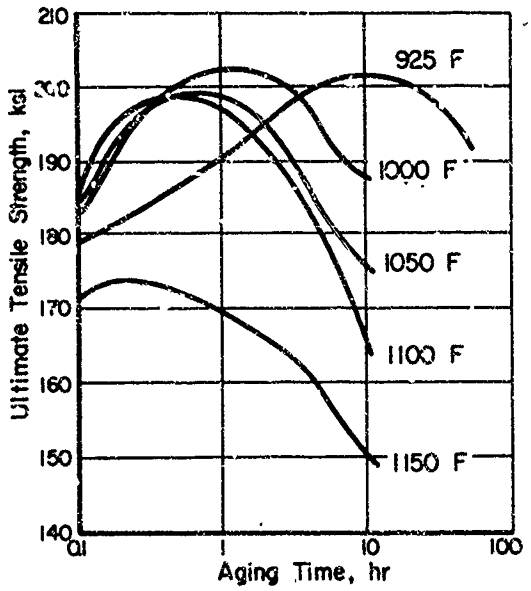

FIGURE 1-7.6.3.3.2-1. AGE HARDENING CHARACTERISTICS OF Ti-4Al-3Mo-1V SHEET.

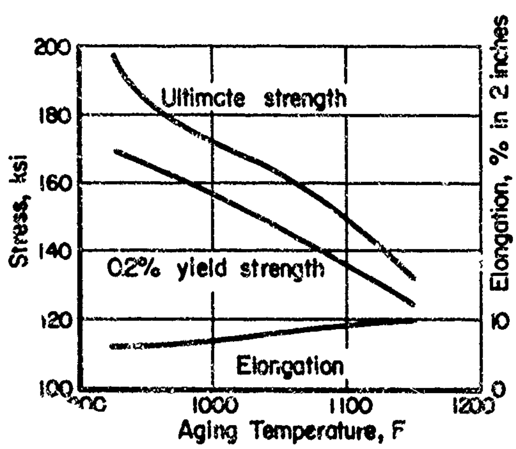

FIGURE 1-7.6.3.3.2-2. EFFECT OF AGING TEMPERATURE (12-HOUR CYCLE) ON THE PROPERTIES OF Ti-4Al-3Mo-1V ALLOY SOLUTION HEAT TREATED AT 1640 F AND WATER QUENCHED(1)

1-7.6.4 Stability

The stability of the Ti-4Al-3Mo-1V alloy in a variety of environments where time, temperature, stress, and media chemistry are variables, has

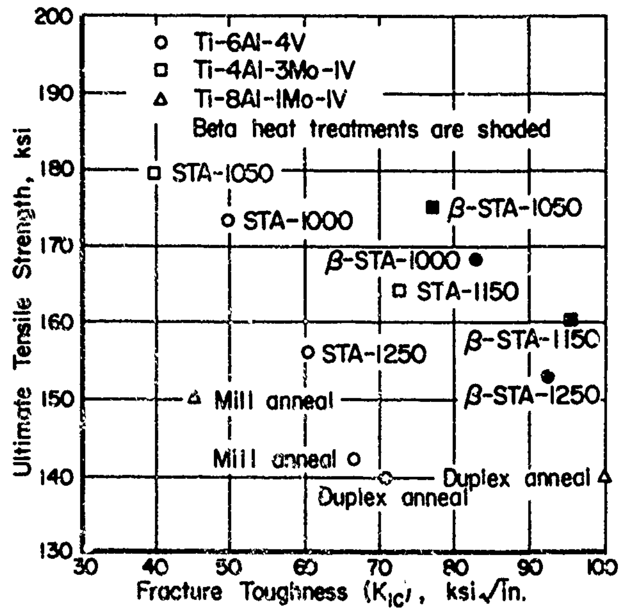

FIGURE 1-7.6.3.3.2-3. STRENGTH-TOUGHNESS COMBINATION FOR SEVERAL TITANIUM ALLOYS AFTER CONVENTIONAL PROCESSING AND HEAT TREATMENT AND SPECIAL BETA PROCESSING AND HEAT TREATMENT(2)

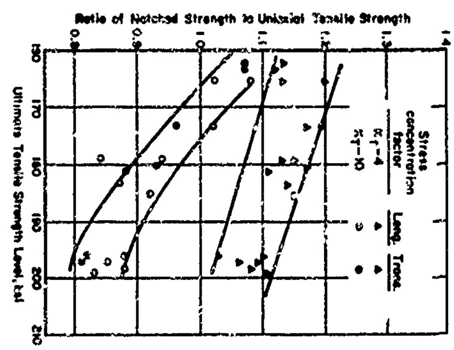

FIGURE 1-7.6.3.3.2-4. NOTCHED-STRENGTH RATIO VERSUS UNIAXIAL-AGED-STRENGTH LEVEL FOR Ti-4Al-3Mo-1V AFTER CONVENTIONAL HEAT TREATMENT(1)

been recorded. Some environments can cause softening and weakening (e.g., excessive elevated temperatures), while others can cause a loss of toughness and ductility (e.g., media promoting stress corrosion). In general, however, the Ti-4Al-3Mo-1V alloy is capable of maintaining strength to quite high service temperature and is noted for its resistance to stress corrosion in environments that promote this type of failure in some other commercial titanium alloys.

1-7.6.4.1 Thermal Stability

It has been previously mentioned that the Ti-4Al-3Mo-1V alloy will begin to age at about

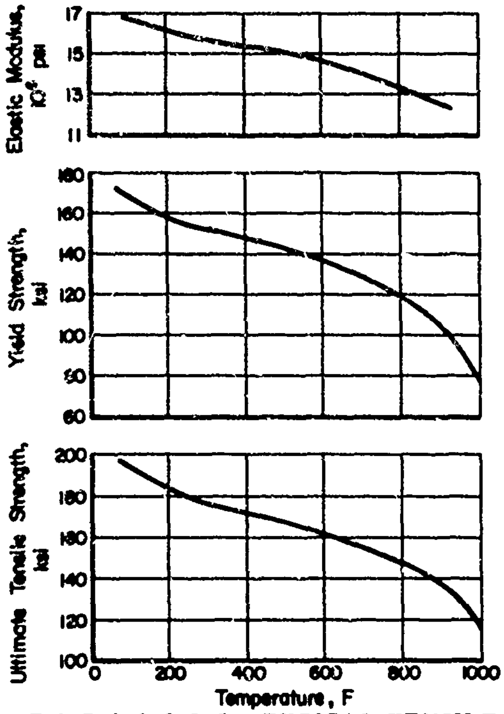

FIGURE 1-7.6.3.3.2-5. TYPICAL TENSILE PROPERTIES OF Ti-4Al-3Mo-1V ALLOY AFTER CONVENTIONAL SOLUTION-ANNEALING PLUS AGING TREATMENTS[1]

600 F in the solution-heat-treated condition. Thus, although the alloy is not put in service in the solution-treated condition, the stability of solution-treated material would be apparent up to about 600 F by lack of property changes. Similarly, solution-heat-treated and aged material does not show appreciable changes in properties in exposures at temperatures up to about the aging temperature (925 F) when stress levels are low. With increasing stress and time of exposure, small changes in properties begin to occur. Table 1-7.6.4.1-1 gives data indicating the extent of such changes in tensile properties for material in the conventional solution-heat-treated plus aged condition. These changes in properties are within the acceptable limits of stable behavior.

At higher temperatures than the conventional aging temperature, the strength of solution heat treated and aged material deteriorates rapidly. This effect is shown by the data plotted in Figure 1-7.6.4.1-1.

The metallurgical thermal stability of the Ti-4Al-3Mo-1V alloy in the duplex annealed or in the beta-processed plus solution-treated and overaged conditions (see Sections 1-7.6.3.2 and 1-7.6.3.3) has been revealed in 450 F tests (at 25 ksi sustained load) for times up to 5000 hours and in 550 F tests (also at 25 ksi) for times up to 2500 hours. Only minor changes in the ultimate tensile strengths and fracture toughness (as indicated by stress intensity factors) occurred in these exposures as shown by the summary data in Figure 1-7.6.4.1-2.

1-7.6.4.2 Chemical Stability

The Ti-4Al-3Mo-1V alloy is not markedly different from other titanium alloys in chemical activity. That is, the alloy's resistance to general corrosion in the usual chemical environments is good, and oxidation resistance up to about 1000 F is normal. The alloy is susceptible to hot-salt stress-corrosion attack and aqueous stress-corrosion under severe conditions. However, The Ti-4Al-3Mo-1V alloy is noted for its good resistance to stress-corrosion of both the above types compared with some of the other titanium alloys.

Several different testing techniques can be used to show the susceptibility of titanium alloys to stress-corrosion phenomena. Time, temperature, stress, and chemical composition of the environment are important variables as is also the state of stress imposed on samples. Sample geometry and any defects within the sample have similarly been recognized to exert significant influence upon the performance of materials in stress-corrosion tests. In addition, a dynamic environment, that is one which is subject to cyclic temperature, time or load and chemistry variations has been found to give results differing from

TABLE 1-7.6.4.1-1. 1000-HOUR STRESSED STABILITY OF Ti-4Al-3Mo-1V SHEET IN THE SOLUTION-HEAT-TREATED PLUS AGED CONDITION[1]

1000-Hour Exposure Conditions		Room-Temperature Properties after Exposure		
Temp, F	Stress, psi	0.2% Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, % in 2 in.
--None--		167,000	190,000	7
500	100,000	170,000	190,000	7
600	95,000	179,000	191,000	6
700	70,000	169,000	188,000	6
800	45,000	164,000	188,000	6
900	20,000	155,000	169,000	8

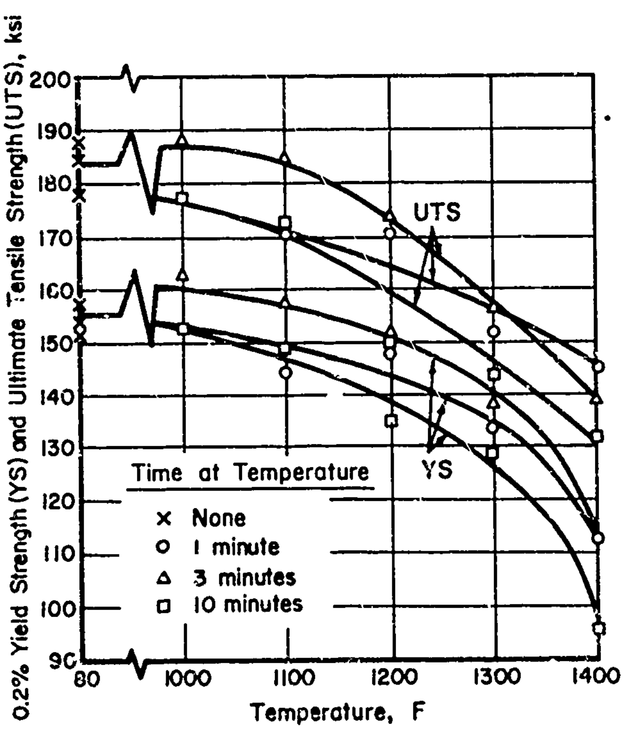

FIGURE 1-7.4.1-1. TENSILE STRENGTHS OF CONVENTIONALLY SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V SHEET AFTER EXPOSURE TO THE VARIOUS TEMPERATURES FOR VARIOUS TIMES(3)

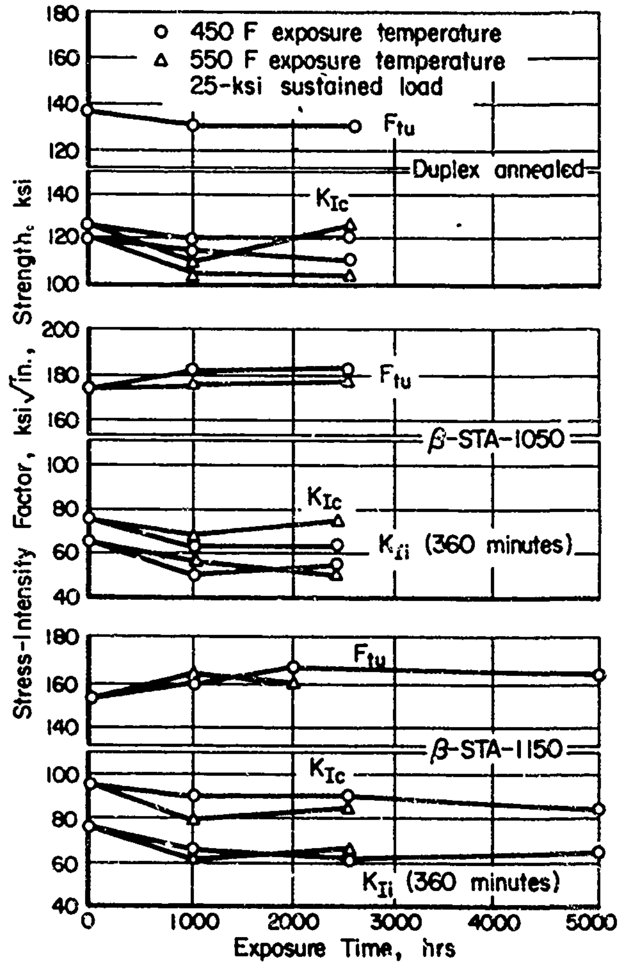

FIGURE 1-7.6.4.1-2. EFFECT OF TIME, TEMPERATURE, AND STRESS ON PROPERTIES OF Ti-4Al-3Mo-1V(2)

those obtained in static environments. Although not all of the variables have been examined for the Ti-4Al-3Mo-1V alloy, the results available do indicate a high resistance of the Ti-4Al-3Mo-1V alloy in the environments which produce stress-corrosion in some other grades.

The apparent resistance of the Ti-4Al-3Mo-1V alloy to hot-salt stress-corrosion was shown previously in Figure 1-4.6.4.2-2. In this test, the Ti-4Al-3Mo-1V alloy in the 1050 F aged condition did not lose any bend ductility when covered with a baked-on salt slurry and exposed to 550 F under 100-ksi stress for times up to 7000 hours. Based on the results of cyclic tests conducted for such alloys as Ti-6Al-4V and Ti-8Al-1Mo-1V, no stress corrosion would be expected in Ti-4Al-3Mo-1V alloy in 550 F cyclic testing.

The susceptibility of titanium alloys to accelerated crack growth in certain media at room temperature was initially demonstrated in 3.5 percent salt solution. This media was found to be about as severe as any in promoting crack-growth acceleration. This phenomenon has been judged by many to be a form of stress-corrosion.

Environmental crack-growth resistance is established by sustained loading of fracture-toughness samples in aqueous media to stress-intensity levels that are specific percentages of the critical stress-intensity level of samples tested in air. The time required for specimen failure is plotted as a function of the applied stress-intensity level, as illustrated in Figure 1-4.6.2.3-4. The resulting curve represents the time required to propagate subcritical cracks to the critical size. For titanium alloys, subcritical crack growth does not occur below a particular stress-intensity level. Since this level is reached before 360 minutes of loading time in the above illustration, the environmental crack-growth resistance parameters, K_i (360 minutes) K_{Ii} (360 minutes), are considered threshold levels.

The threshold stress level at which a fatigue crack of given length in Ti-4Al-3Mo-1V alloy

becomes unstable in a 3.5 percent NaCl solution is compared with other titanium alloys in Figure 1-4.6.4.2-5. Figure 1-4.6.2.2-6 shows tensile strength-threshold stress-intensity-level comparisons for the same group of alloys in various heat-treated condition. The superior resistance to salt-solution-type stress corrosion of beta-processed Ti-4Al-3Mo-1V alloy is evident.

1-7.7 SELECTED REFERENCES

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(2) "Boeing Model 2707 Airframe Design Report Part D, Materials and Processes", Report V2-B2707-8, Contract FA-SS-66-5, The Boeing Company (September 6, 1966).

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1-8 Titanium Alloy Ti-679

1-8.0 GENERAL REMARKS

The Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si alloy is best known by its common numerical name, 679, that is the alloy development number originally assigned to this composition by its British developers, and will henceforth be referred to by this name in this section. The 679 alloy is quite unique among the commercial titanium grades due to the low aluminum and high tin contents and because of the intentional silicon addition. The 679 alloy is licensed for manufacture in the U.S.A., as well as being available on an import basis from Britain. It is essentially an engine alloy and is available in bar and billet form for such purposes.

1-8.1 COMMERCIAL DESIGNATIONS

Designations	Producer	Forms Available[a]
IMI 679	Imperial Metals Industries, Ltd. (Br.)	B, b
Ti-679	Titanium Metals Corp.	B, b

(a) B = billet, b = bar.

1-8.2 ALTERNATE DESIGNATIONS (COMMON NAMES)

679

1-8.3 ALLOY TYPE

Near alpha, alpha-beta

1-8.4 COMPOSITION, RANGE OR MAXIMUMS, %

Major Elements

Al	2.0-2.5
Sn	10.5-11.5
Zr	4.0-6.0
Mo	0.8-1.2
Si	0.15-0.27
Fe	0.120 max

Interstitial Elements

C	0.04 max
N	0.04 max
O	--
H	0.008 max

1-8.5 SPECIFICATIONS

None

1-8.6 DESCRIPTION AND METALLURGY

1-8.6.1 Composition and Structure

The 679 alloy is unique in comparison with United States developed titanium alloys inasmuch as it contains a very high tin content (11 percent) and a silicon addition, the latter resulting in compound formation. The aluminum, tin, and zirconium contents are collectively alpha-phase stabilizing, while the molybdenum addition is beta-phase stabilizing and the silicon is compound forming The net effect of these additions is a weakly beta-stabilized alpha-beta alloy with intermetallic compound fortification. Because of the predominance of the alpha phase in the structures and the lean beta-stabilizer content, the alloy also has been loosely classified in the family of super-alpha alloys. For the same reason [illegible]s also been termed a near-alpha, alpha-beta alloy. The small silicon addition should not be lightly regarded in referring to the alloy with either the near-alpha or super-alpha terminology since the presence of intermetallic compound in the structure is a potent ingredient in promoting good creep properties. Thus, while the above common classifications are appropriate, the fact that the alloy structure is fortified with compound should be appreciated in the selection of this grade for possible applications.

The 679 alloy displays the isothermal transformation chatacteristics of two-phase alpha-beta alloys. A time-temperature-transformation curve for Ti-679 has been determined and is shown in Figure 1-8.6.1-1. The main features of the diagram are the beta-transus temperature range (1730 ±15 F) and the short-time transformation of beta to alpha at 1400 F. Since some beta phase is present and stable even at room temperature, a true alpha transus does not exist. However, above a certain temperature the beta is insufficiently rich in beta stabilizer so that, upon quenching, it transforms to alpha prime at the Ms temperature. Below that temperature, the beta is retained on quenching. This is the temperature indicated as the alpha-prime transus. The beta that is retained on quenching is quite ductile and soft.

The microstructures resulting from quenching above the beta-transus temperature to room temperature are martensitic. Alpha plus beta (plus compound) microstructures wherein the beta is transformed (martensite) result from exposure at 1700 F and quenching. Quenching to 1100 and 1700 F exposure and holding for about 5 minutes isothermally results in a completely martensitic structure on subsequent quenching to room temperature. Equilibrium alpha-plus compound

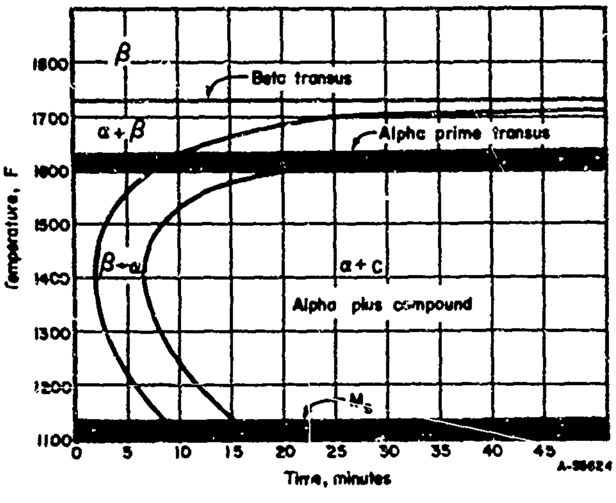


FIGURE 1-8.6.1-1. TIME-TEMPERATURE-TRANSFORMATION CHARACTERISTICS OF Ti-679 ALLOY[1]

structures, wherein the alpha is a mixture of large, isothermally transformed platelets and fine martensitic alpha, are formed by holding at temperatures within the alpha-plus compound region.

An intermetallic compound, believed to be the silicide Ti_5Si_3, is present in all room-temperature microstructures, regardless of cooling rates or beta treatments. The silicon particles are considerably mobile at temperatures in the beta field and high in the alpha-plus-beta field. By slow cooling from the all-beta phase through the alpha-plus-beta temperature region, the silicides will agglomerate, or migrate, to the prior beta-grain boundaries. Slow cooling from high in the alpha-plus-beta field does not result in this agglomeration of silicides at prior beta-grain boundaries. This appears to indicate at least a partial dissolution of the silicide in the all-beta-phase field.[1]

Ti-679, when rapidly quenched from the beta field, transforms to martensite between 1100 and 1200 F. The silicides act as nucleation sites for the transformation. Several alpha platelets originate at each one of these silicide sites. Silicon is in this respect a grain refiner, and macrostructures of Ti-679 large bar and billet are thus extremely fine grained.[1]

1-8.6.2 Deformation Practice and Effects

To obtain optimum properties with the 679 alloy, the material is usually forged at a 1650 F finishing temperature. Initial rough forging may be done as high as 1825 F, but the maximum temperature for finishing is 1690 F. Large amounts of forging work, that is reductions of about 8 to 1 in upsetting, for example, result in structures having the best combinations of properties.

1-8.6.3 Heat-Treatment Practice and Effects

1-8.6.3.0 General Remarks

The 679 composition is amenable to a variety of heat treatments to result in a range of mechanical properties. High strengths in combination with lower ductility than obtained with the lower strength conditions are possible but are not so often used as the medium-strength condition. As with other alpha-beta alloys, maximum strength is developed in the solution-heat-treated and aged condition. Aging response is dependent upon cooling rate from the solution temperature as well as on the solution temperature per se. Annealing of the 679 alloy is similar to solution treating and aging, inasmuch as a two-stage treatment is preferred: a high-temperature solutionizing treatment followed by a lower temperature stabilizing anneal. Good combinations of properties are available from both conditions.

1-8.6.3.1 Stress-Relief Annealing

Stress-relief annealing of 679 material may be accomplished by exposure to the aging or stabilization annealing (synonomous) temperature, that is 930 F, for a 10-hour period. Such an exposure would restore heat-treated properties to the material after a stress-inducing operation such as a machining operation. In some applications, the stress-relief annealing operation may be incorporated into the final heat treatment by machining, etc., prior to the final 10 hours of exposure at 930 F.

1-8.6.3.2 Annealing

The preferred annealing treatment of 679 alloy is a duplex treatment consisting of a high-temperature exposure followed by a low-temperature stabilization exposure. Exposure for 1 hour at 1650 F followed by air cooling results in an equiaxed alpha-plus-transformed-beta structure having dispersed silicide particles throughout. During the air cooling, alpha precipitates from regions that were beta at the annealing temperature. The beta regions then become sufficiently rich in beta-stabilizer content to be retained upon further cooling to room temperature. The second part of the duplex-annealing cycle is used to convert the metastable alpha-beta mixture to a more stable alpha-plus-beta structure. A 24-hour exposure at 930 F is used to accomplish this. Additional alpha is rejected from the metastable beta to form a stable alpha-plus-beta-plus compound structure.

1-8.6.3.3 Strengthening Heat Treatments

While the beta stabilizer content of the 679 alloy is lean, the combined effect of the molyb-

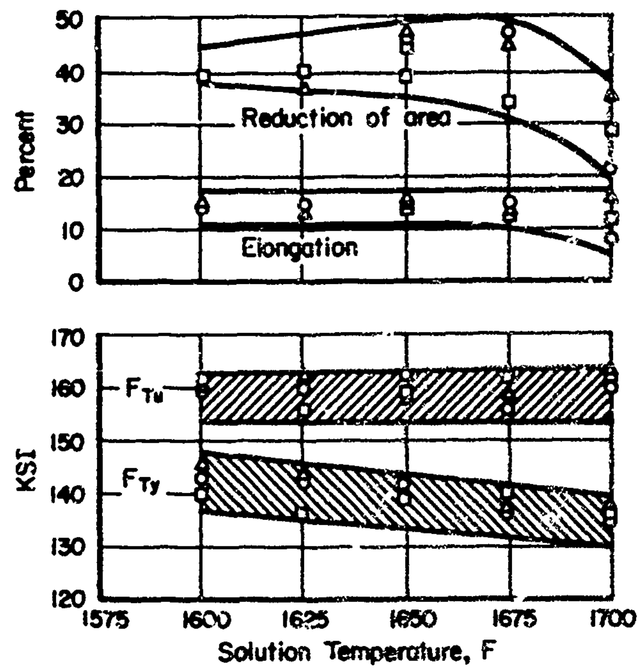
denum, silicon, tin, and zirconium content is to permit appreciable heat-treatment response. As mentioned previously, cooling rate is very important. This is accounted for by the rapidity of the beta-to-alpha transformation in the intermediate temperature range (see Figure 1-8.6.4-1). If the cooling rate through this intermediate temperature range is quite rapid, appreciable strengthening is possible during subsequent aging.

1-8.6.3.3.1 Hardenability

The 679 alloy is not especially noted for its deep hardenability. However, appreciable section thicknesses can be raised to quite high strengths, as indicated by the data given in Table 1-8.6.3.3.1-1.

1-8.6.3.3.3 Aging Heat Treatments

The 679 alloy may be solution heat treated from a range of temperatures between about 1550 and 1675 F. As the 1700 F solution temperature is approached, ductility values are lowered, probably because of the increased acicularity of the structure and the unfavorable alpha-beta ratio. The effect is illustrated in Figure 1-8.6.3.3.2-1 for air-cooled samples and in Table 1-8.6.3.3.2-1 for water-quenched material. The effect of cooling rate from the solution temperature is to control the amount of aging response possible with the material. Fast cooling as in water quenching, of course, permits the largest response, as shown by the data given in Table 1-8.6.3.3.2-2. The reasons for the variable response are clearly seen by superimposing cooling rate curves over the TTT diagram presented in Figure 1-8.6.3.3.2-2. Considering these points, a preferred solution temperature of 1650 F has been recommended (a 1-hour exposure for the larger sections is preferred). The 930 F aging response (24-hour exposure) after solution heat treatment and air



Symbol	Heat Treatment
O	1/2 AC
▢	1 AC
Δ	2 AC

FIGURE 1-8.6.3.3.2-1. TENSILE PROPERTIES OF SOLUTION-TREATED 1/2-INCH-SQUARE BAR[1]

(Bar originally forged 1-1/8-inch square)

TABLE 1-8.6.3.3.1-1. TENSILE PROPERTIES OF Ti-679 ROLLED BAR AS AGED AT 930 F AFTER AIR COOLING OR OIL QUENCHING FROM 1650 F[1](a)

Diameter of Heat-Treated Section, in.	Air Cooled				Oil Quenched			
	UTS, ksi	YS, ksi	Elong., %	RA, %	UTS, ksi	YS, ksi	Elong., %	RA, %
3(b)	151.0	--	21	42	170.0	142.0	18	40
3(c)	150.5	127.5	18	34	169.0	139.0	16	34
2(c)	158.5	131.5	16	31	174.0	145.0	14	32
1-1/2(c)	160.0	135.5	17	29	179.5	147.0	18	33
1(c)	160.0	134.0	17	31	182.0	150.0	14	31
1/2(c)	166.0	147.0	17	30	194.0	163.0	12	29

(a) All material from rolled bar originally 3 1/2 inches in diameter.
(b) Longitudinal specimen cut from edge of heat-treated cylinder.
(c) Longitudinal specimens cut from center of heat-treated cylinders.

TABLE 1-8.6.3.3.2-1. EFFECT OF SOLUTION TEMPERATURES ON DUCTILITY[a][1]

Solution Temp., F	UTS, ksi	YS, ksi	Elong., %	RA, %
1700	194.6	169.0	6.0	23.7
1675	186.9	168.3	--	--
1625	176.8	151.5	12.0	43.0
1600	176.2	152.0	12.0	41.0
1575	154.8	118.1	19.0	41.8
1550	155.8	104.7	18.0	39.1

(a) All samples water quenched from temperature and not aged.

cooling from the various temperatures is shown in Figure 1-8.6.3.3.2-3. Termination of the solution treatment by water quenching is recommended if high tensile strength is the required criterion. If improved tensile ductility and improved elevated-temperature creep strength are the requirements, air cooling from the solution temperature is desirable.

TABLE 1-8.6.3.3.2-2. AGING RESPONSE OF Ti-679 COOLED FROM 1650 F SOLUTION TEMPERATURE AT VARIOUS RATES[1]

Cooling Method	UTS, ksi	YS, ksi	Elong., %	RA, %
As Forged	151.2	136.5	14.0	49.9
Furnace Cooled + Aged[a]	143.7	132.1	11.0	23.1
Furance Cooled	143.8	133.0	11.0	25.8
Air Cooled + Aged[a]	167.3	149.6	17.5	44.4
Air Cooled	159.8	142.8	16.0	47.4
Water Quenched + Aged[a]	199.6	180.0	10.0	32.9
Water Quenched	176.8	151.5	12.0	43.0

(a) Samples aged for 24 hours at 930 F.

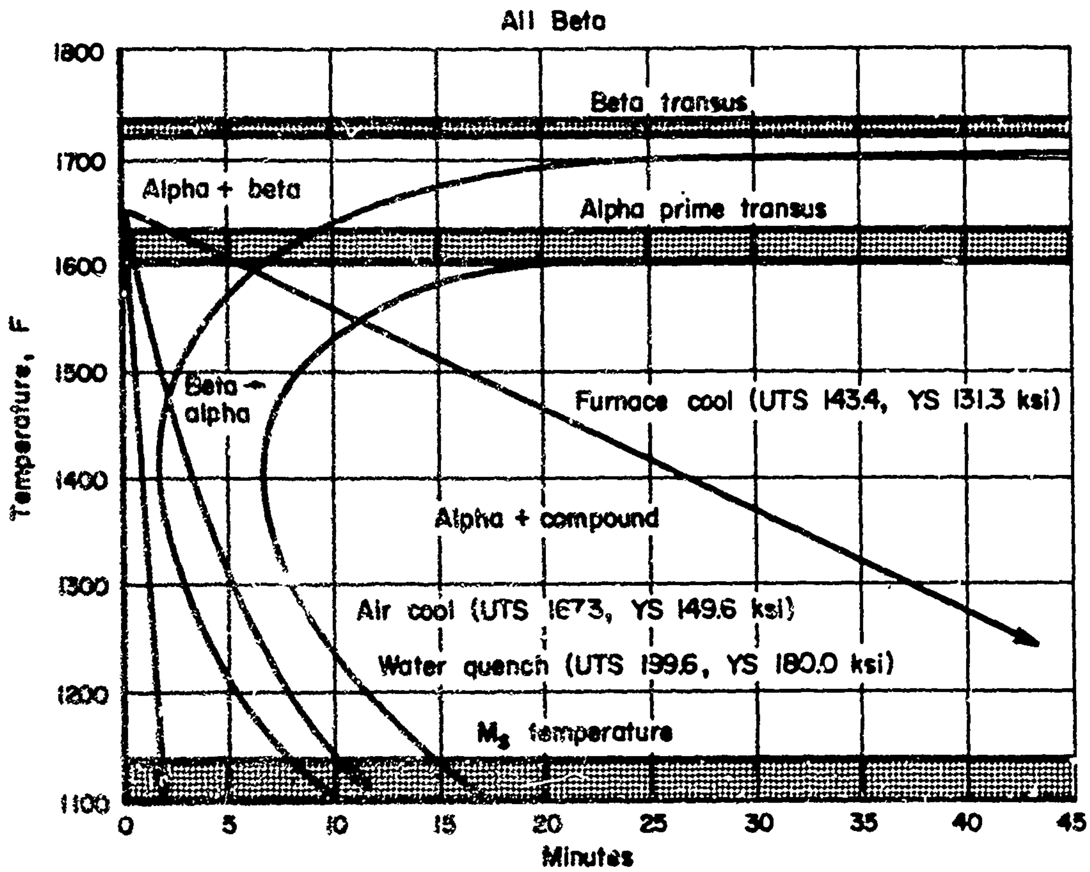
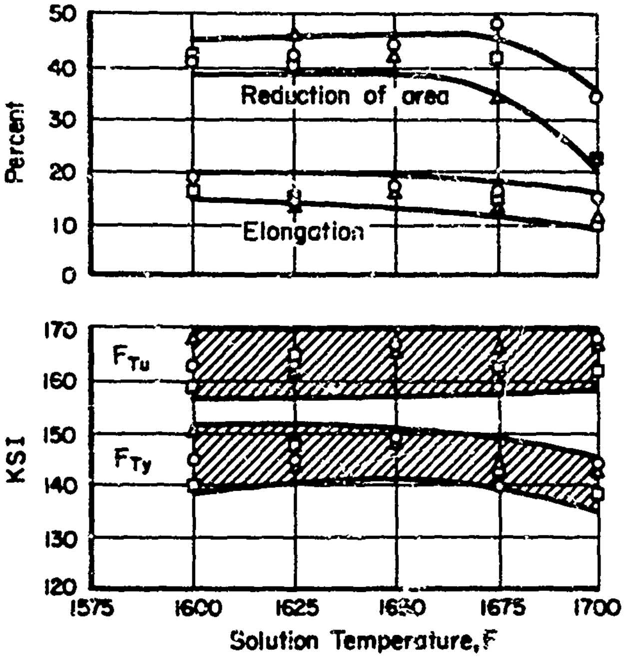


FIGURE 1-8.6.3.3.2-2. COOLING CURVES CORRESPONDING TO COOLING RATES OF Ti-679 FROM 1650 F SOLUTION TEMPERATURE[1] (ALL SAMPLES AGED 930 F -- 24 HOURS)



Symbol	Heat Treatment
O	1/2 AC + 930 F -- 24 AC
▢	1 AC + 930 F -- 24 AC
Δ	2 AC + 930

FIGURE 1-8.6.3.3.2-3. TENSILE PROPERTIES OF SOLUTION-TREATED AND AGED 1/2-INCH-SQUARE BAR[1]

Bar originally forged 1-1/8 inch square.

1-8.6.3.3.3 Aging Heat Treatments

The recommended aging heat treatment for the 679 alloy is 24 hours at 930 F and air cool. The aging temperature is not critical within the range 910 to 950 F. The effect of aging for shorter times at 930 F is to give slightly lower strength as shown in Table 1-8.6.3.3.3-1 and also a less stable structure. Table 1-8.6.3.3.3-1 also shows the effects of a higher aging temperature (1050 F) on tensile properties. Figure 1-8.6.3.3.3-1 shows the short-time tensile properties of Ti-679 alloy from room temperature to 1000 F while Figure 1-8.6.3.3.3-2 shows typical creep strength characteristics of forged and heat treated compressor wheel material.

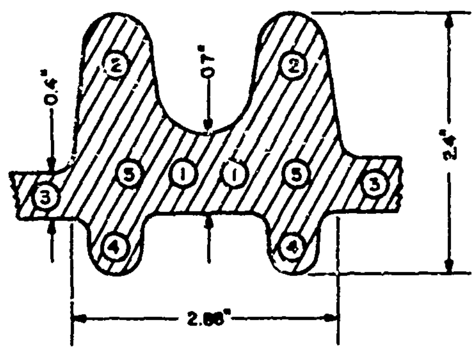
1-8.6.4 Stability

The thermal and chemical stability for the 679 alloy have been found to be quite good for this high-strength composition. Stability is the measure of property changes experienced upon exposure to environments other than ambient environments where time, temperature, stress, and exposure media are important variables.

TABLE 1-8.6.3.3.3-1. TENSILE PROPERTIES OF WATER-QUENCHED Ti-679 FORGING AFTER VARIOUS AGING CYCLES[1]

Location[a]	Aging Temp, F	Aging Time, hr	UTS, ksi	YS, ksi	Elong., %	RA, %
1	930	1	176.8	154.4	12.0	41.0
3	930	1	180.5	165.1	12.0	45.3
5	930	1	162.9	139.8	14.0	48.0
1	930	12	179.6	158.0	12.0	40.0
3	930	12	191.9	169.4	11.0	41.4
5	930	12	167.8	145.2	18.0	47.0
1	930	24	178.8	158.0	11.0	40.0
3	930	24	192.9	170.9	10.0	35.3
5	930	24	173.9	151.7	10.0	42.0
1	1050	24	178.0	161.0	10.0	33.5
3	1050	24	179.2	156.0	16.0	42.1
5	1050	24	175.1	154.6	12.0	32.2

(a) See figure below.



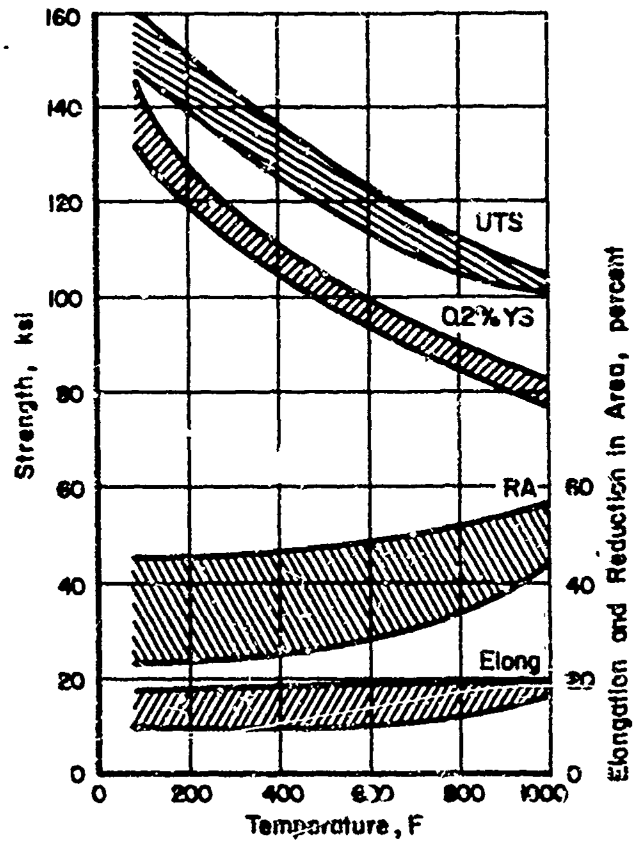


FIGURE 1-8.6.3.3.3-1. SHORT-TIME TENSILE PROPERTIES OF Ti-679 FORGED COMPRESSOR WHEELS AS-SOLUTION HEAT TREATED 1 HOUR AT 1650 F, AC, THEN AGED 24 HOURS AT 930 F, AC[1,2]

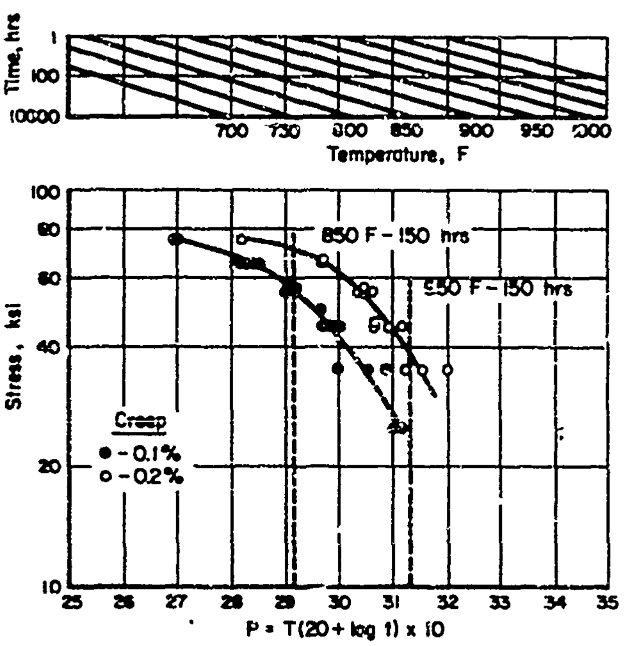


FIGURE 1-8.6.3.3.3-2. LARSEN-MILLER PARAMETER VERSUS STRESS CURVES FOR CREEP IN Ti-679 COMPRESSOR WHEEL FORGINGS AS-SOLUTION HEAT TREATED 1 HOUR AT 1650 F, AC, THEN AGED 24 HOURS AT 930 F, AC[1]

1-8.6.4.1 Thermal Stability

The typical test for the thermal stability of 679 not only includes a long-time exposure at an elevated temperature, but also an imposed stress under such conditions as would be found in service. The stability of 679 alloy heat treated in the form of jet-engine compressor wheels has been found to be good at least up to temperatures of 900 F as shown by the data given in Table 1-8.6.4.1-1. Instability for this alloy has been found at 950 and 1000 F exposures in 100 hours or less. Since the greatest variation in stability appeared at 950 F, this appears to be the threshold temperature for instability. Results of tests at 900 F exposure temperature indicated no instability for times up to 1000 hours.

1-8.6.4.2 Chemical Stability

The 679 alloy has the usual resistance to corrosion in a variety of chemical media as observed for the other commercial titanium grades. The high tin content of the Ti-679 alloy promotes the free-scaling characteristic of this alloy at elevated temperatures in oxidizing environments. While the free-scaling characteristic is desirable, this trait is accompanied by the resistance to deep penetration of contamination during elevated-temperature exposure for the same reason. That is, the high tin content imparts a resistance to contamination of the surface layers at the same time as it gives the 679 alloy the free-scaling characteristic. The threshold temperature and stress for inception of salt-stress corrosion has been determined for Ti-679. The technique was to use a variable-width sheet specimen that allowed accurate measurement of the critical stress level with a minimum number of samples. The critical stress level is defined as the minimum stress required to initiate stress corrosion at a given temperature and elapsed time (2500 hours). A dye penetrant was used in connection with microscopic examination to determine cracking. Figure 1-8.6.4.2-1 shows the results of this examination. Two other commercial alloys are included for comparison. As can be seen, Ti-679 has superior salt-stress-corrosion resistance.

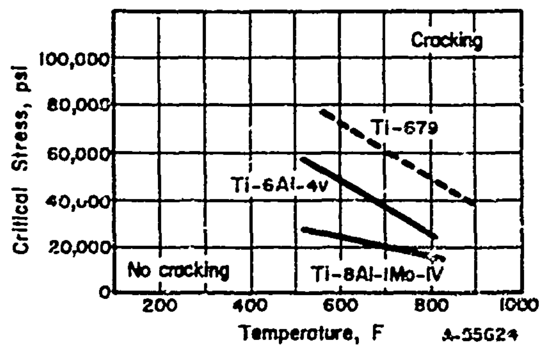


FIGURE 1-8.6.4.2-1. HOT-SALT STRESS-CORROSION CRACKING OF TITANIUM ALLOYS[1]

1-8.7 SELECTED REFERENCES

(1) "Metallurgical and Mechanical Properties of Titanium Alloy Ti-679", Titanium Metals Corporation of America Data Sheet.

(2) "Ti-679, High Temperature Titanium Alloy for Short-Time Strength, Creep and Stability", Titanium Metals Corporation of America Data Sheet.

(3) "Recent Developments in Titanium Alloys for Long Time Elevated-Temperature Applications", Titanium Metals Corporation of America Data Sheet (August, 1964).

(4) "IMI-679", Imperial Metals Industries (Kynock), Limited, Data Sheet.

(5) "How to Use Titanium -- Properties and Fabrication of Titanium Mill Products", Titanium Metals Corporation of America Brochure.

(6) Erdeman, V. J., "A Titanium Alloy for Use at Elevated Temperatures", Metal Progress (February, 1966).

TABLE 1-8.6.4.1-1. STABILITY OF Ti-679 ALLOY COMPRESSOR-BLADE MATERIAL AFTER SELECTED CREEP EXPOSURES[a]

Location	Direction	Creep Exposure Temp, F	Creep Exposure Stress, ksi	Creep Exposure Time, hr	Post-Creep Tensile Properties: Plastic Deformation, %	YS (0.2%), ksi	UTS, ksi	Elong., %	RA, %
Typical Unexposed Properties					--	138.0	155.0	13.0	30.0
Web	Radial	800	75	150	0.15	141.2	155.5	16.0	36.7
Web	Radial	800	75	150	0.16	136.7	149.9	12.0	25.5
Rim	Tang.	850	65	150	0.17	140.6	154.2	14.0	3[illegible].7
Rim	Tang.	850	65	150	0.15	141.0	152.9	13.0	29.5
Rim	Tang.	850	65	150	0.13	142.5	156.4	12.0	29.5
Rim	Tang.	850	65	150	0.14	151.0	166.1	14.0	36.2
Rim	Tang.	850	65	150	0.15	144.0	152.9	13.0	29.5
Rim	Tang.	850	65	1000	0.31	138.1	149.9	15.0	30.8
Rim	Tang.	850	65	1000	0.21	141.7	156.0	13.0	28.7
Rim	Tang.	900	50	150	0.13	141.4	157.6	14.0	25.4
Rim	Tang.	900	50	150	0.19	141.2	151.0	10.0	18.3
Coupling	Axial	900	55	150	0.26	137.2	150.3	14.0	31.6
Coupling	Axial	900	55	150	0.21	134.7	149.0	14.0	36.2
Web	Radial	950	45	150	0.24	143.[illegible]	157.7	7.0	7.9
Web	Radial	950	45	150	0.33	136.4	150.7	7.0	6.3
Web	Radial	900	55	150	0.15	147.1	16[illegible].3	12.0	27.5
Web	Radial	900	55	150	0.19	138.4	153.5	10.0	23.4
Rim	Tang.	900	55	150	0.20	141.0	154.2	12.0	25.4
Rim	Tang.	900	55	150	0.16	140.0	154.2	13.0	27.5
Rim	Tang.	900	55	150	0.16	142.0	157.2	12.0	22.6
Rim	Tang.	900	55	1000	0.36	142.1	156.8	15.0	28.9
Coupling	Axial	950	45	150	0.68	133.3	149.4	12.0	17.7
Coupling	Axial	950	45	150	0.37	137.6	151.5	9.0	13.9
Rim	Tang.	950	45	150	0.26	142.7	154.4	10.0	19.8
Rim	Tang.	950	45	150	0.16	140.5	155.0	14.0	28.8
Rim	Tang.	950	45	150	0.24	140.0	156.4	14.0	32.3
Rim	Tang.	950	45	1000	1.67	135.5	149.2	6.0	8.7
Rim	Tang.	1000	35	150	0.88	135.4	147.4	7.0	13.2
Rim	Tang.	1000	35	150	0.34	139.6	151.9	5.0	9.4

(a) Heat treatment: 1650 F (1 hour) AC + 930 F (24 hours) AC.

1-9 Titanium Alloy Ti-6Al-2Sn-4Zr-2Mo

1-9.0 GENERAL REMARKS

The Ti-6Al-2Sn-4Zr-2Mo alloy was developed as another of the so-called "super" alpha alloys for engine use, principally as forgings. However, in addition to its proposed use in bar and forgings, flat-rolled and extruded products also have been proposed. These products are characterized by their high strength and stability at temperatures up to 1050 F. At this time, only one grade is produced that is essentially a high-purity grade and the material is carefully processed to guarantee a premium product.

1-9.1 COMMERCIAL DESIGNATIONS

Designation	Producer	Forms Available[a]
Ti-6Al-2Sn-4Zr-2Mo	Titanium Metals Corporation	B,b,S,E
RMI-6Al-2Sn-4Zr-2Mo	Reactive Metals, Inc.	B,b

(a) B = billet, b = bar, S = sheet, E = extrusions.

1-9.2 ALTERNATE DESIGNATIONS (common names)

6-2-4-2.

1-9.3 ALLOY TYPE

Near alpha, alpha-beta.

1-9.4 COMPOSITION, RANGE OR MAXIMUMS, %

Major Elements

Al	5.5-6.5
Sn	
Zr	3.6-4.4
Mo	1.8-2.2
Fe	0.25 max

Interstitial Elements

C	0.05 max
N	0.05 max
O	0.12 max
H	0.0100 max (billet)
	0.0125 max (bar)
	0.0150 max (sheet)

1-9.5 SPECIFICATIONS

MIL-T-9046F.

1-9.6 DESCRIPTION AND METALLURGY

1-9.6.1 Composition and Structure

The 6 percent aluminum addition in the Ti-6Al-2Sn-4Zr-2Mo composition is a potent alpha-phase stabilizer, while the 2 percent molybdenum addition represents only a moderate quantity of this potent beta-phase stabilizer. The tin and zirconium additions are solid-solution strengthening elements that are neutral with respect to phase stabilization. The net effect of this combination of alloying elements is the generation of a weakly beta-stabilized, alpha-beta alloy. Since it is weakly beta stabilized, the alloy is also properly described as a near-alpha, alpha-beta alloy. This term is frequently referred to in abbreviated form as simply "near alpha" and the Ti-6Al-2Sn-4Zr-2Mo alloy is popularly classified with the "super" alpha compositions.

The Ti-6Al-2Sn-4Zr-2Mo alloy evolved from from research conducted to improve upon the properties inherent in high-aluminum-content titanium compositions, principally high strength at elevated temperatures. However, the requirement for high strength at both room temperature and 1000 F existed as did the need for a composition having greater thermal stability than the high-aluminum-content binary alloys. The additions of molybdenum, tin, and zirconium to the Ti-6Al base gave this new alloy the balance to satisfy these requirements. The beta-stabilizing addition, molybdenum, increases room- and elevated-temperature tensile strength and enhances stability while the combination of aluminum, tin, and zirconium maintain the long-time (creep) elevated-temperature strength. The increase in density resulting from the 8 percent-heavier metal additions (tin, zirconium, and molybdenum) is small, while the increase in toughness due to these additions is significant. Since the combination of alloying elements net only a weakly stabilized beta content, the alloy is weldable.

The effect of aluminum in this composition on the allotropic transformation in titanium is to stabilize the alpha phase and increase the beta transus temperature to about 1815 F. Variations in alloy composition and, in particular, variations in oxygen content, affect the beta transus temperature. Oxygen and aluminum are strong alpha-phase stabilizers. Tin, zirconium, and especially molybdenum tend to lower the beta-transus temperature.

The transformation kinetics of Ti-6Al-2Sn-4Zr-2Mo have been studied by conventional quench techniques to produce a time-temperature-transformation diagram such as that shown in Figure 1-9.6.1-1. The study has placed the M_s temperature at about 1470 F and the M_f temperature at about 1415 F. Transformation by nucleation and growth is very rapid.

The structures of Ti-6Al-2Sn-4Zr-2Mo alloy are typically massive equiaxed alpha in a transformed beta matrix. The equiaxed alpha grains in sheet product tend to be smaller than found in forgings, and to be present in greater proportion than in forgings. Primary alpha is typically about 80 to 90 percent of the structure in sheet and can range somewhat lower than this in forged product. As in other near-alpha alloys, small amounts of residual beta phase can be observed metallographically within the transformed beta portion of the structure. The occurrence is typically between the acicular alpha grains of the transformed phase.

1-9.6.2 Deformation Practice and Effects

The forging of Ti-6Al-2Sn-4Zr-2Mo alloy has been accomplished at temperatures high in the alpha-beta region successfully. Closed-die forgings were upset-blocked from 1775 F and finished from 1750 F using typical titanium forging procedure. Conversion of ingot to billet can be done at higher starting temperatures with finishing temperatures selected to provide a mixed alpha-beta structure in the product shipped. The forging of the Ti-6Al-2Sn-4Zr-2Mo alloy entirely within the beta region has been briefly reported (see Table 1-9.6.4.1-7). As with other high-strength titanium alloys this technique may offer certain advantages to the forgers and may provide a desirable combination of properties in addition to better creep strength.

Very little information is available on the fabrication of Ti-6Al-2Sn-4Zr-2Mo sheet. The heat-treatment temperatures recommended have been designed for compatibility with hot sheet forming and sizing operations. On this basis, sheet forming between 1450 and 1100 F is suggested. Depending upon the severity of the forming required, a high or low temperature within this range could be selected. The guaranteed room-temperature, minimum-bend radius for sheet product is between 4.5 and 5T.

1-9.6.3 Heat-Treatment Practice and Effects

1-9.6.3.0 General Remarks

A variety of heat treatments for the Ti-6Al-2Sn-4Zr-2Mo alloy are possible. A particular condition is usually selected on the basis of type product, part section size, and properties desired.

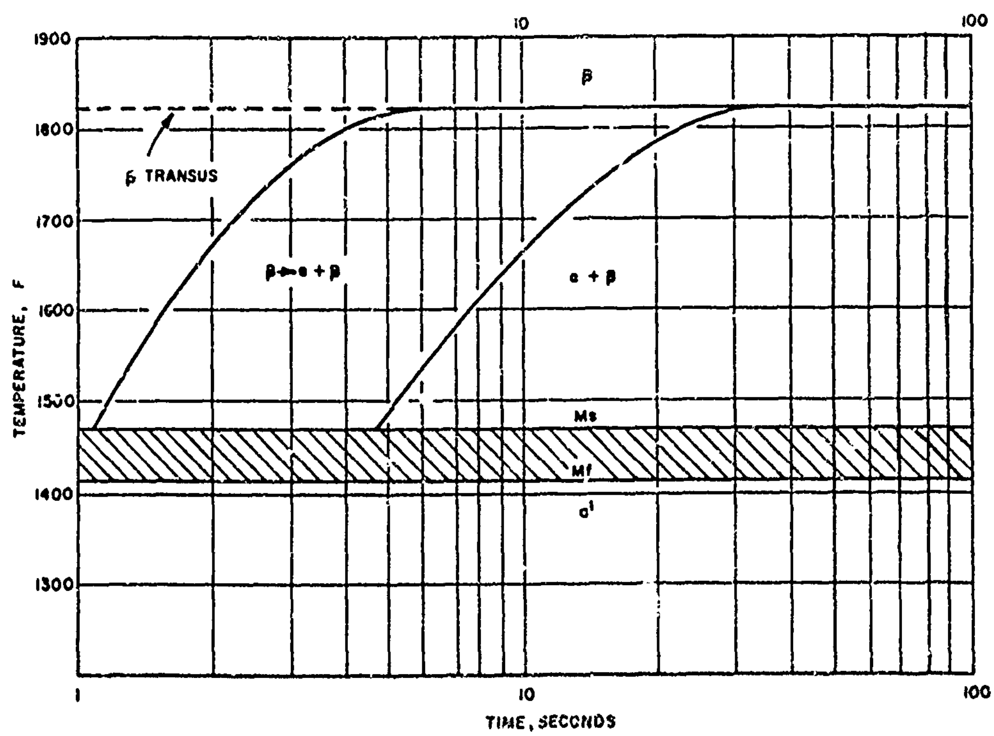


FIGURE 1-9.6.1-1. ISOTHERMAL TIME-TEMPERATURE-TRANSFORMATION DIAGRAM FOR Ti-6Al-2Sn-4Zr-2Mo(1)

1-9.6.3.1 Stress-Relief Annealing

A stress-relief-annealing temperature range for this alloy is 900 to 1200 F. A 1 to 4-hour exposure within this temperature range is recommended. Obviously, a stress-relief-annealing condition should be selected on the basis of what portion of the residual stress it is desirable to reduce. No information is available on the absolute reduction of residual stress using particular stress-relieving treatments.

1-9.6.3.2 Annealing

Several different annealing treatments are available for the Ti-6Al-2Sn-4Zr-2Mo alloy. Choice depends upon the product form and the section size of the product as well as on the properties desired. A general annealing treatment is offered by the producer that consists of a 1 to 8-hour exposure at 1300 to 1550 F followed by slow cooling to 1050 F and subsequent air cooling. For bar and forged sections, solution annealing for 1 hour at 1650 to 1750 F plus stabilization annealing for 8 hours at 1100 F and air cooling is recommended. In this condition, the guaranteed room-temperature properties of 1-inch-diameter bar are as follows:

130 ksi ultimate tensile strength,
120 ksi 0.2 percent yield strength,
10 percent elongation, and 20 percent reduction in area.

Two thermal treatments have been developed for sheet that involve two-part or three-part heat treatment as follows:

Duplex annealing: 1/2 hour, 1650 F, AC, plus 1/4 hour, 1450 F, AC

Triplex annealing: 1/2 hour, 1650 F, AC, plus 1/4 hour, 1450 F, AC, plus 2 hours, 1100 F, AC.

Each of the heat-treated conditions offers excellent high-temperature strength and stability combined with good fracture toughness at lower temperatures. The advantage of triplex annealing is in higher uniaxial strength at room temperature. For sheet less than 0.125 inch in thickness, shorter annealing time at 1650 F than indicated above is recommended. Ten minutes at temperature has been suggested. Room and elevated-temperature tensile properties for Ti-6Al-2Sn-4Zr-2Mo alloy sheet are shown in Figure 1-9.6.3.2-1. Creep data are summarized using the Larson-Miller treatment in Figure

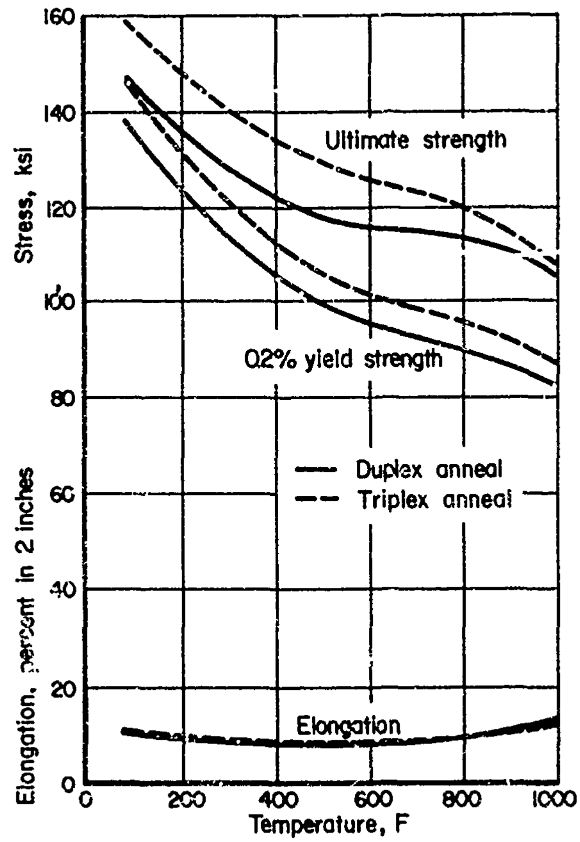


FIGURE 1-9.6.3.2-1. ROOM AND ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Ti-6Al-2Sn-4Zr-2Mo SHEET[1]

Section size is a criterion for the selection of the high temperature annealing portion of duplex annealing for bar and forgings as indicated below:

Bar and forged sections less than 2.5 inches in diameter	1 hour, 1750 F, AC + 8 hours, 1100 F, AC
Bar and forged sections greater than 2.5 inches in diameter	1 hour, 1650 F, AC + 8 hours, 1100 F, AC or 1 hour, 1750 F, AC + 8 hours, 1100 F, AC

The 1650 F treatment, along with the 1100 F stabilization anneal, provides somewhat higher tensile strengths at room and elevated temperatures while the 1750 F treatment combined with 1100 F stabilization as above results in superior creep resistance at the higher temperatures,

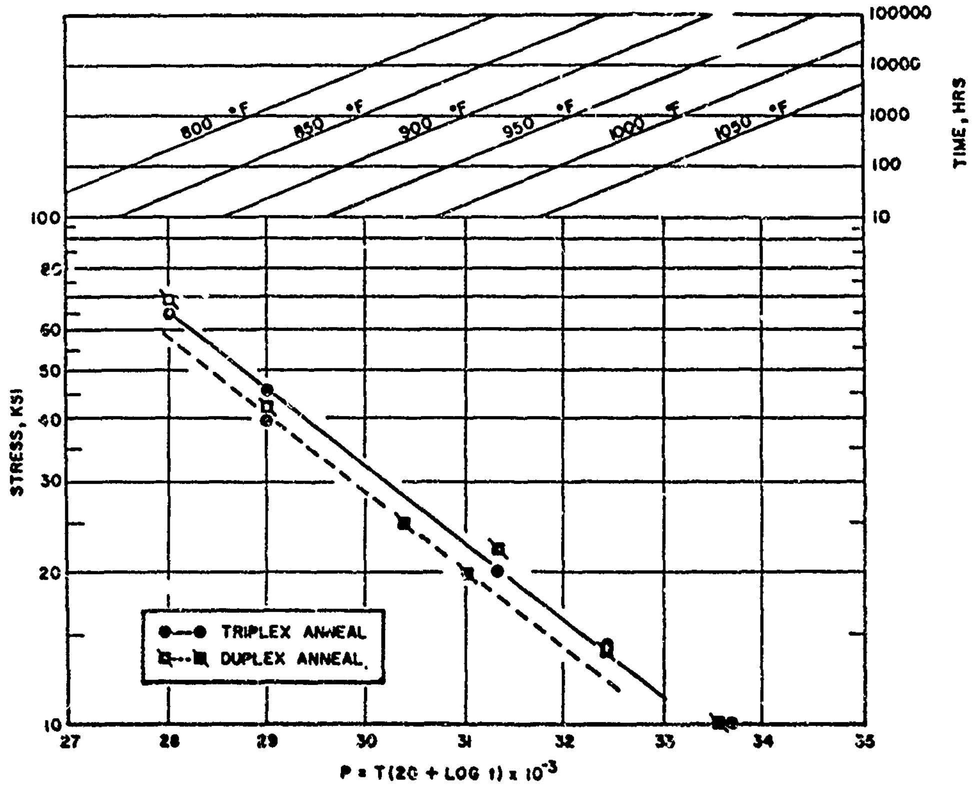


FIGURE 1-9.6.3.2-2. LARSON-MILLER PRESENTATION OF 0.1 PERCENT CREEP DATA FOR Ti-6Al-2Sn-4Zr-2Mo SHEET(1)

improved stability, and slightly higher room-temperature, notched-stress, rupture strength. Undoubtedly, temperatures above and below 1750 F would give slightly different alpha to beta ratios and therefore result in different strengths after subsequent aging. Additional recommendations for heat treatments of this kind can be requested from the producers.

Room and elevated-temperature tensile properties for Ti-6Al-2Sn-4Zr-2Mo bar and forgings are shown in Figures 1-9.6.3.2-3 and -4. Larson-Miller-type treatment of bar and forging creep data is presented in Figure 1-9.6.3.2-5.

1-9.6.3.3 Strengthening Heat Treatments

The Ti-6Al-2Sn-4Zr-2Mo alloy may be heat treated to obtain higher uniaxial tensile strengths by conventional solution heat treatment and aging exposures. Since the beta content in this alpha-beta alloy is small, the response to such a strengthening heat treatment is not large. Further, the material in the STA condition has lower creep strength than in the annealed-plus-stabilized condition.

1-9.6.3.3.1 Solution Annealing

The preferred solution-heat-treatment temperature for the Ti-6Al-2Sn-4Zr-2Mo alloy is 1750 F. Exposure at this temperature is typically 1 hour and the treatment is terminated by water quenching.

1-9.6.3.3.2 Aging Heat Treatments

After solution heat treatment at about 1750 F and water quenching, the Ti-6Al-2Sn-4Zr-2Mo alloy will respond to aging in the 1000 to 1100 F temperature range with a substantial increase in tensile strength. Average tensile-property values obtained from a compressor wheel forging in the STA condition are compared with the same material as annealed in Figure 1-9.6.3.3.2-1. However, the disadvantage of the STA condition in creep for this same material is illustrated in Figure 1-9.6.3.3.2-2.

1-9.6.4 Stability

The thermal and chemical stability for the Ti-6Al-2Sn-4Zr-2Mo alloy have been rather

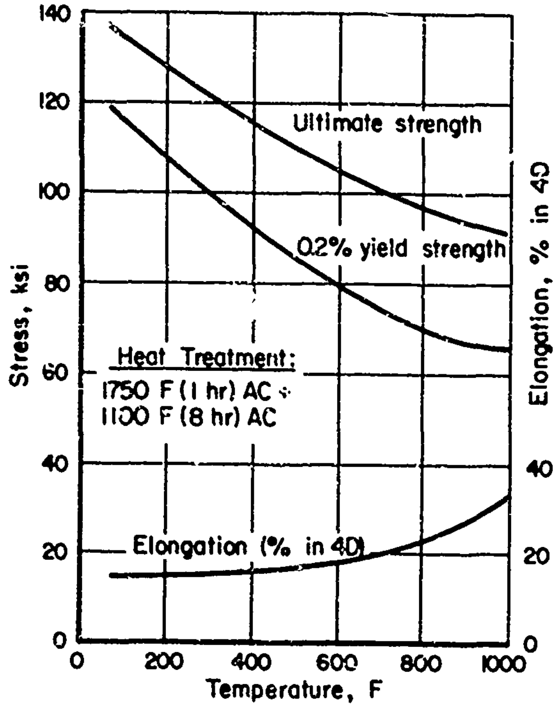


FIGURE 1-9.6.3.2-3. ROOM AND ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Ti-6Al-2Sn-4Zr-2Mo BARSTOCK 2-1/4 INCHES IN DIAMETER(1)

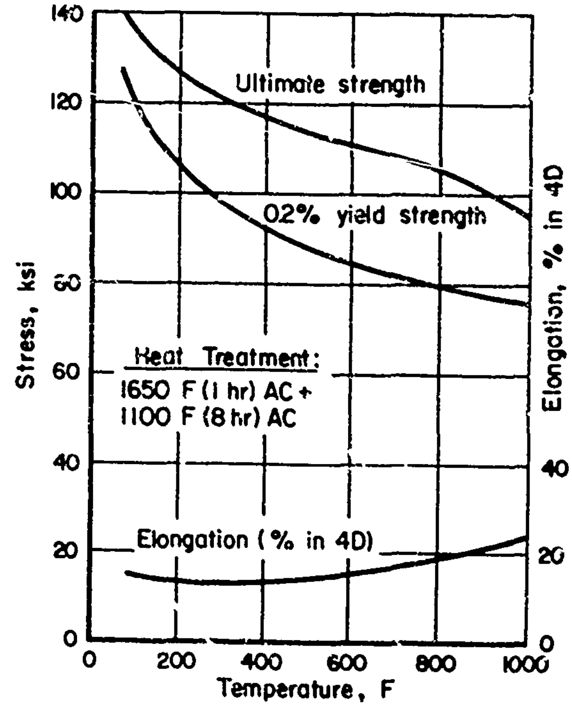


FIGURE 1-9.6.3.2-4. ROOM AND ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Ti-6Al-2Sn-4Zr-2Mo FORGED COMPRESSOR WHEEL(1)

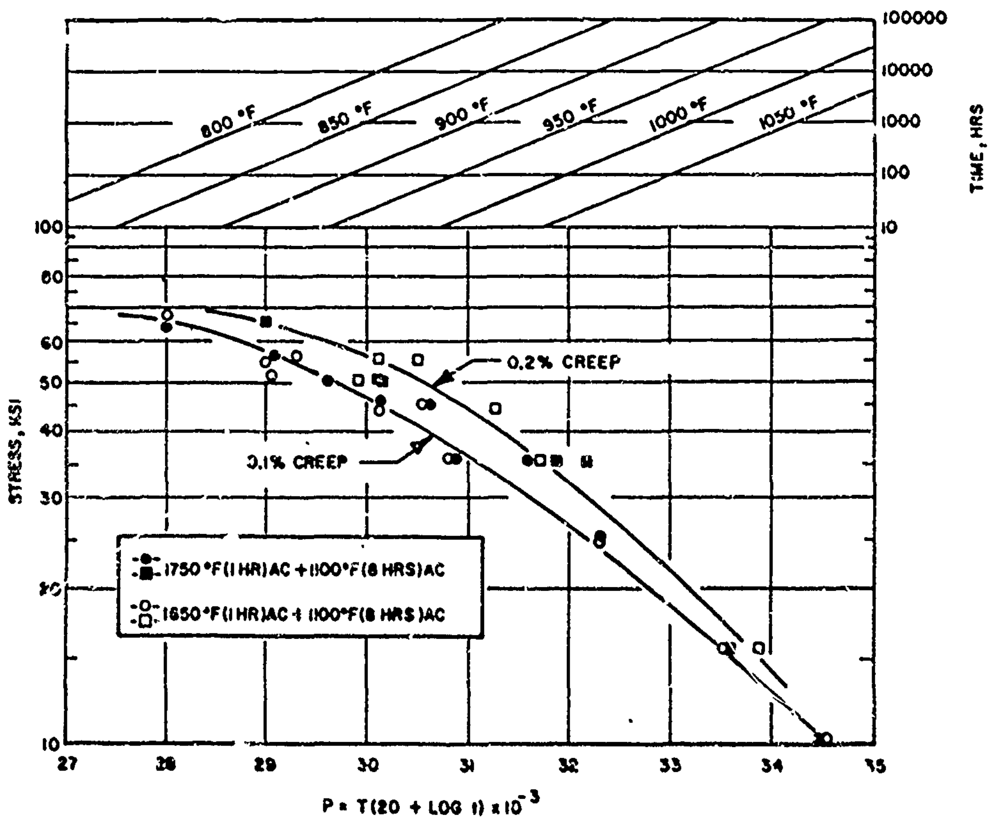


FIGURE 1-9.6.3.2-5. LARSON-MILLER PRESENTATION OF CREEP DATA FOR BAR AND FORGED SECTIONS OF Ti-6Al-2Sn-4Zr-2Mo(1).

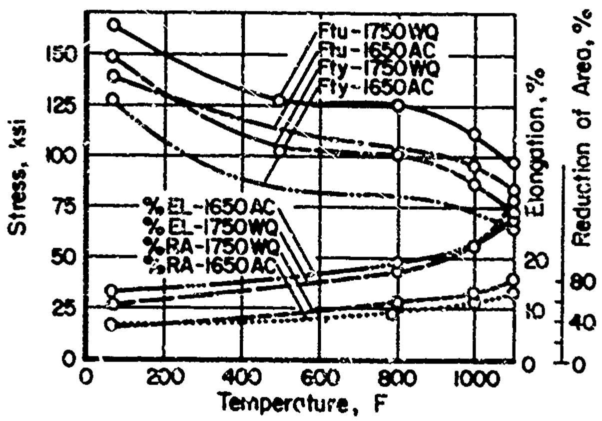


FIGURE 1-9.6.3.3.2-1. TENSILE PROPERTIES VERSUS TEMPERATURE FOR MATERIAL FROM A Ti-6Al-2Sn-4Zr-2Mo COMPRESSOR WHEEL FORGING(2)

(Average of radial and axial tests. Material aged 1100 F, 8 hr, and air cooled.)

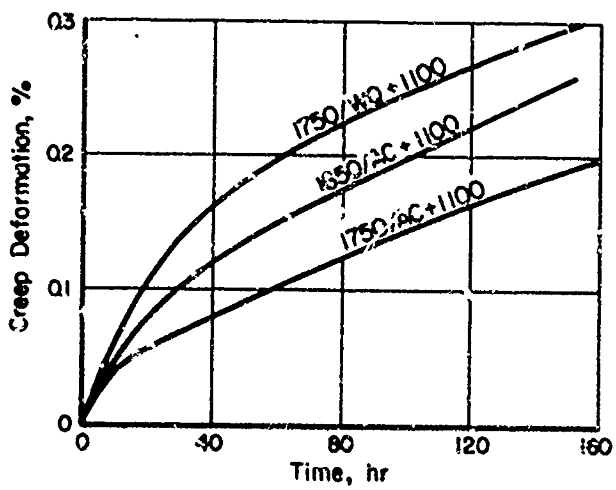


FIGURE 1-9.6.3.3.2-2. TYPICAL CREEP CURVES FROM A Ti-6Al-2Sn-4Zr-2Mo FORGING(2)

(900 F, 50 ksi exposure.)

thoroughly researched for this comparatively new composition. Complete stability is meant as no change in material characteristics due to an exposure involving temperature and/or chemical media different from ambient conditions. Also, length of exposure as well as the stress imposed on the material are important factors. One of the important features of the Ti-6Al-2Sn-4Zr-2Mo alloy is that it shows very attractive stability in a variety of exposure environments.

1-9.6.4.1 Thermal Stability

A large number of data have been generated in determining the thermal stability of Ti-6Al-2Sn-4Zr-2Mo material under demanding temperature-stress-time exposure conditions. The data are given for sheet, rolled bar, forged bar, and forged sections in Tables 1-9.6.4.1-1 through 1-9.6.4.1-7. Additional long-time-exposure data(3) are summarized below for samples from 1-3/8-inch bar stock that had been heat treated 1 hour at 1775 F, air cooled, and aged 8 hours at 1100 F followed by air cooling.

Stability Exposure	Time to 0.1% Deformation, hr	Total Plastic Deformation, %	Room-Temperature Tensile Properties After Exposure: UTS, ksi	YS (0.2%), ksi	El[illegible], %	RA, %
3000 hours at 825 F and 47.5 ksi	185	0.276	156	145	13	23
	--	0.192	155	142	14	19
2300 hours at 925 F and 27.5 ksi	98	0.436	157	149	16	32
	--	0.240	160	151	18	38

The test results indicate a capability of application at temperatures up to 1050 F, and outstanding post-exposure, room-temperature, tensile results up to this temperature. Stability is apparent by comparing the favorable values of post-exposure ductility and strength with those of the unexposed material.

1-9.6.4.2 Chemical Stability

While definitive data are not available, it is believed that the properties of the Ti-6Al-2Sn-4Zr-2Mo alloy are not adversely affected by the small amount of surface oxide formed during exposure to service temperatures. Also, it is believed that the alloy has essentially the same corrosion resistance as all titanium alloys to most organic salts and acids.

The resistance of Ti-6Al-2Sn-4Zr-2Mo alloy to accelerated crack propagation in aqueous environments (i.e., salt-water, stress-corrosion phenomenon) has not been reported. However,

TABLE 1-9.6.4.1-1. 1000-HOUR ELEVATED-TEMPERATURE THERMAL STABILITY OF Ti-6Al-2Sn-4Zr-2Mo SHEET(a)

Heat Treatment	Thermal Exposure	Specimen Direction	Room-Temperature Smooth and Notched Tensile Properties After Thermal Exposure: UTS, ksi	YS (0.2%), ksi	Elong., %	NTS,(b) ksi	Ratio, NTS/YS
1650 F, 1/2 hr, AC + 1450 F, 1/4 hr, AC + 1100 F, 2 hr, AC	None	L	158.7	149.9	11.0	147.4	0.98
		T	156.5	147.4	13.0	147.1	1.00
	600 F, 1000 hr	L	159.6	150.4	13.5	155.2	1.03
		T	159.7	149.7	11.5	143.0	0.96
	800 F, 1000 hr	L	161.5	151.7	15.0	153.2	1.01
		T	159.2	150.3	14.5	146.4	0.97
	900 F, 1000 hr	L	165.8	160.0	14.5	151.5	0.95
		T	163.2	157.6	14.0	148.0	0.95
	1000 F, 1000 hr	L	165.0	159.6	13.0	125.4	0.79
		T	163.9	158.3	13.0	104.1	0.66
1650 F, 1/2 hr, AC + 1450 F, 1/4 hr, AC	None	L	147.7	139.1	13.0	145.9	1.05
		T	147.5	138.0	13.5	138.8	1.01
	600 F, 1000 hr	L	163.3	152.3	8.5(c)	145.6	0.95
		T	161.6	149.5	10.5	137.7	0.92
	800 F, 1000 hr	L	168.6	154.8	13.5	142.4	0.92
		T	168.5	154.9	10.5	136.6	0.88
	900 F, 1000 hr	L	167.8	161.3	10.5	145.9	0.90
		T	168.9	161.7	14.0	137.6	0.85
	1000 F, 1000 hr	L	165.7	160.0	12.0	133.7	0.84
		T	162.9	158.1	13.0	128.9	0.82

(a) 0.036-inch-thickness sheet. All specimens acid pickled 0.002 per surface after exposure prior to tensile tests.
(b) K_t = 17 min.
(c) Broke at end of gage length.

TABLE 1-9.6.4.1-2. 1000-HOUR ELEVATED-TEMPERATURE STRESS STABILITY OF Ti-6Al-2Sn-4Zr-2Mo SHEET(a)

Heat Treatment	Stability Exposure Conditions: Temp, F	Stress, ksi	Time, hr	Plastic Deformation, %	Room-Temperature Tensile Properties After Stressed Exposure: UTS, ksi	YS (0.2%), ksi	Elong., %
1650 F, 1/2 hr, AC + 1450 F, 1/4 hr, AC		None		--	147.7	139.1	13.0
	800	40	1000	0.11	164.4	149.2	13.5
	900	20	1000	0.14	162.6	154.7	6.0
	950	15	1000	0.16	162.9	157.8	7.0(b)
	1000	10	1000	0.25	160.7	159.7	3.0(b)
1650 F, 1/2 hr, AC + 1450 F, 1/4 hr, AC + 1100 F, 2 hr, AC		None		--	156.8	150.2	14.0
	800	40	1000	0.04	159.8	149.6	14.0
	900	20	1000	0.08	161.3	152.8	11.0
	900	20	1000	0.10	161.5	155.3	18.5
	900	20	1000(c)	0.08	159.3	150.9	16.0
	950	15	1000	0.20	161.7	155.0	12.0
	950	15	1000	0.15	165.1	138.5	15.5
	950	15	1000(c)	0.15	160.5	152.3	18.0
	1000	10	1000	0.20	158.5	157.0	4.5
	1000	10	1000	0.16	162.9	160.0	18.0
	1000	10	1000(c)	0.22	162.7	154.5	14.5

(a) 0.040-inch-thick longitudinal specimens.
(b) Broke at end of gage length.
(c) Surface conditioned by acid pickling 0.002 inch per surface prior to tensile testing. All other tensile tests conducted on the as-exposed surface.

TABLE 1-9.6.4.1-3. ELEVATED-TEMPERATURE STRESS STABILITY OF Ti-6Al-2Sn-4Zr-2Mo TRIPLEX-ANNEALED SHEET(1)

Sheet Thickness, in.	Stability Exposure Conditions Temp, F	Stress, ksi	Time, hr	Specimen Direction	Plastic Deformation, %	Room-Temperature Tensile Properties After Stressed Exposure UTS, ksi	YS (0.2%), ksi	Elong., %
0.036		None		L	--	158.7	149.9	11.0
				T	--	156.5	147.4	13.0
	800	65	150	L	0.06	166.5	152.9	12.0
				T	0.07	163.9	151.0	15.0
	900	45	150	L	0.16	167.6	156.0	13.0
				T	0.17	163.9	151.0	15.3
	1000	25	150	L	0.30	167.7	154.3	13.5
				T	0.31	164.5	153.2	14.8
0.08		None		L	--	160.2	145.9	12.3
				T	--	147.6	135.3	11.8
	800	65	150	L	0.05	162.5	146.2	18.0
				T	0.10	148.3	134.7	15.5
	900	45	150	L	0.12	162.2	145.5	18.5
				T	0.14	148.5	135.4	14.5(a)
	1000	25	150	L	0.25	165.5	152.5	10.5
0.125		None		L	--	145.6	133.5	14.7
				T	--	149.6	135.4	15.2
	800	65	150	L	0.06	146.8	135.3	20.0
				T	0.06	151.2	136.3	16.0
	900	45	150	L	0.19	148.2	134.4	20.0
				T	0.14	151.5	137.6	21.5
	1000	25	150	L	0.22	149.1	136.7	18.5
				T	0.19	152.5	138.2	20.0

(a) Broke at end of gage length.

TABLE 1-9.6.4.1-4. ELEVATED-TEMPERATURE STRESS STABILITY OF Ti-6Al-2Sn-4Zr-2Mo ROLLED BAR(1,3)

Heat Treatment	Bar Diameter, in.	Stability Exposure Conditions Temp, F	Stress, ksi	Time, hr	Plastic Deformation, %	Room-Temperature Tensile Properties After Stressed Exposure(a) UTS, ksi	YS (0.2%), ksi	Elong., %	RA, %
1650 F, 1 hr, AC + 1100 F, 8 hr, AC	1-1/8		None		--	152.6	140.5	20.2	41.2
	1-1/8	900	45	150	0.14	145.7	133.0	17.0	45.0
	1-1/8	1000	25	150	0.19	145.9	136.3	15.0	42.0
	2-1/4		None		--	143.2	127.1	15.0	24.7
	2-1/4	800	65	150	0.17	139.6	129.3	16.0	32.1
	2-1/4	900	45	150	0.13	141.6	126.8	14.0	31.4
	2-1/4	1000	25	150	0.14	143.3	134.4	13.0	30.7
	2-1/4	1100	10	150	0.14	135.3	123.7	14.0	24.0
1750 F, 1 hr, AC + 1100 F, 8 hr, AC	2-1/4		None		--	141.4	125.8	15.0	24.7
	2-1/4	800	65	150	0.12	137.1	123.2	16.0	33.7
	2-1/4	900	45	150	0.12	135.8	121.7	15.0	28.2
	2-1/4	1000	25	150	0.11	140.4	127.6	18.0	33.4
	2-1/4	1100	10	150	0.11	137.8	128.2	16.5	33.5

(a) Specimens tested in the as-exposed condition.

TABLE 1-9.6.4.1-5. 1000-HOUR ELEVATED-TEMPERATURE STRESS STABILITY OF Ti-6Al-2Sn-4Zr-2Mo ROLLED BAR[a]

Stability Exposure Conditions			Plastic Deformation,	Room-Temperature Tensile Properties After Stressed Exposure[b]			
Temp, F	Stress, ksi	Time, hr	%	UTS, ksi	YS (0.2%), ksi	Elong., %	RA, %
	None		--	137.0	120.7	15.5	30.7
800	55	1000	0.11	147.4	132.3	15.5	34.3
850	50	1000	0.15	143.6	132.2	18.5	34.8
900	50	1000	0.17	142.4	129.1	17.5	28.9
1000	15	1000	0.12	142.1	131.2	15.0	31.6

(a) Outside longitudinal specimens from 2-1/4-inch-diameter bar, heat treated 1650 F, 1 hr, AC + 1100 F, 8 hr, AC.
(b) Specimens tested in the as-exposed condition.

TABLE 1-9.6.4.1-6. ELEVATED-TEMPERATURE STRESS STABILITY OF FORGED 3-INCH SQUARE Ti-6Al-2Sn-4Zr-2Mo BAR[a]

Heat Treatment	Specimen Location and Direction	Stability Exposure Conditions			Plastic Deformation,	Room-Temperature Tensile Properties After Stressed Exposure[b]			
		Temp, F	Stress, ksi	Time, hr	%	UTS, ksi	YS (0.2%), ksi	Elong., %	RA, %
1650 F, 1 hr, AC + 1100 F, 8 hr, AC	OL		None		--	146.2	135.5	16.5	39.9
	OT		None		--	143.5	130.8	14.0	30.2
	CT		None		--	144.5	135.5	17.0	43.3
	OL	800	65	150	0.01	143.0	134.0	19.0	41.6
	OT	1000	25	150	0.19	146.8	136.5	16.0	26.1
	OL	1100	10	150	0.23	141.0	134.1	16.5	35.4
	CT	900	45	150	0.14	142.2	132.2	18.0	47.0
1750 F, 1 hr, AC + 1100 F, 8 hr, AC	CL		None		--	138.5	129.3	19.0	39.2
	CT		None		--	137.8	128.5	16.0	30.7
	OL	800	65	150	0.08	139.6	129.5	18.0	37.3
	OL	1100	10	150	0.32	138.5	131.2	17.0	35.4
	OT	1000	25	150	0.17	141.4	131.6	14.5	32.8
	CT	900	45	150	0.14	137.6	127.3	15.0	33.5

(a) Heat treated as 7-inch-long full sections.
(b) Specimens tested in the as-exposed condition.

TABLE 1-9.6.4.1-7. 1000-HOUR ELEVATED-TEMPERATURE STRESS STABILITY OF Ti-6Al-2Sn-4Zr-2Mo FORGED SECTIONS[a]

Specimen Grain Structure	Stability Exposure Conditions			Plastic Deformation,	Room-Temperature Tensile Properties After Stressed Exposure[c]			
	Temp, F	Stress, ksi	Times, hr	%	UTS, ksi	YS (0.2%), ksi	Elong., %	RA, %
Equiaxed		None		--	143.5	131.9	17.0	43.4
Transformed[b]		None		--	141.1	129.0	13.5	43.0
Equiaxed	800	65	1000	0.195	142.4	131.4	20.0	40.6
Transformed	800	65	1000	0.113	141.3	130.4	17.0	39.8
Equiaxed	900	50	1000	0.250	148.9	134.1	17.0	36.2
Transformed	900	50	1000	0.168	149.4	136.9	18.0	28.1

(a) All specimens heat treated 1750 F, 1 hr, AC + 1100 F, 8 hr, AC.
(b) Average of duplicate tests.
(c) Specimens tested in the as-exposed condition.

based on the good behavior of similar compositions in salt-water testing by the Navy,[4] it is believed that the Ti-6Al-2Sn-4Zr-2Mo alloy would be relatively insensitive to stress-corrosion of this type. These investigators[4] found that the following alloys were insensitive:

Ti-7Al-2.5Mo	Ti-6Al-4V
Ti-6Al-2Mo	Ti-6Al-2Sn-1Mo-3V
Ti-6Al-2Sn-1Mo-1V	Ti-5Al-2Sn-2Mo-2V
Ti-6.5Al-5Zr-1V	

The criteria for insensitivity in the Navy tests were: (1) little or no loss in nominal bend strength, (2) nonaccelerated or normal crack propagation rates, and (3) normal appearance of the fracture surface (in tests conducted in a sea water environment). Thus, it is readily apparent that the Ti-6Al-2Sn-4Zr-2Mo alloy fits within the group of insensitive compositions above and that in lieu of test data the best estimate is that the alloy is insensitive to aqueous environment stress corrosion.

The critical stress level required to cause cracking during elevated-temperature exposure to chloride containing environments is one measure of an alloy's resistance to hot-salt stress corrosion. In this test, time, temperature, and stress as well as environmental media are interrelated. Threshold values of each parameter can be determined to define the sensitivity of a composition to the hot-salt cracking phenomenon. In tests conducted on the Ti-6Al-2Sn-4Zr-2Mo alloy, the results appear to show a relative insensitivity of this composition to hot-salt cracking. The test data are shown in comparison with test data for two other commercial alloys in Figure 1-9.6.4.2-1. It should be emphasized that these results were obtained in a test representing very severe conditions (e.g., saturated salt solutions applied directly to the sample in copious amounts). Further, the occurrence of the phenomenon in service is extremely rare if not entirely unknown. Hot salt stress corrosion is principally a laboratory phenomenon, although consideration of its possible occurrence should be allowed for in the design of hardware.

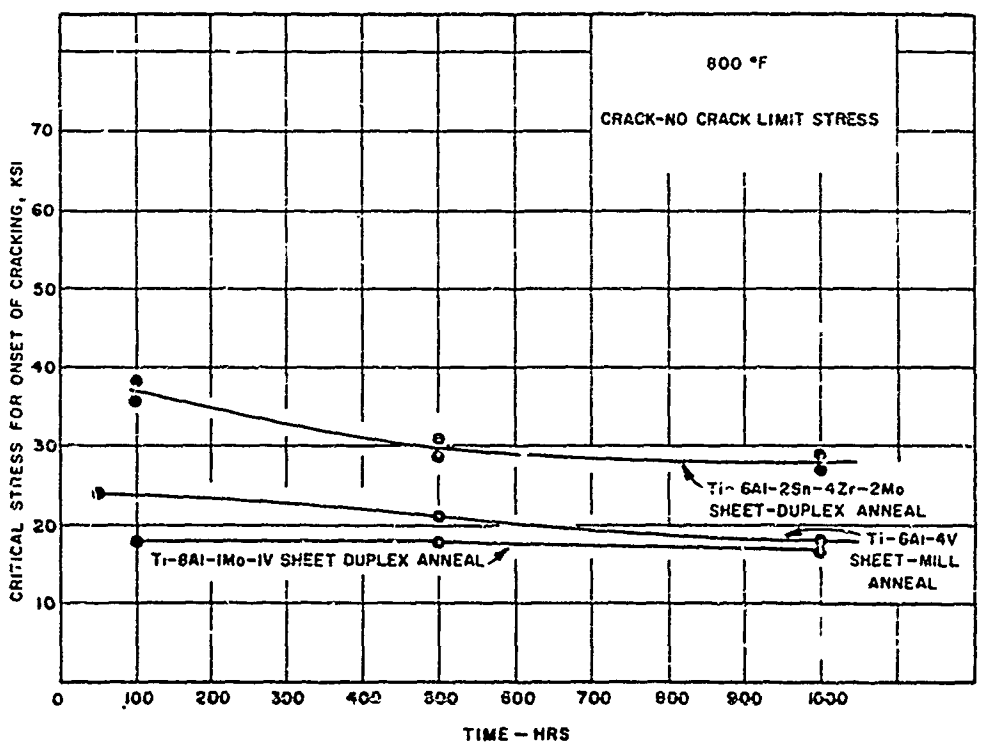


FIGURE 1-9.6.4.2-1. 800 F SALT SCREENING TEST RESULTS FOR Ti-6Al-2Sn-4Zr-2Mo IN COMPARISON WITH TWO OTHER COMMERCIAL ALLOYS[1]

1-9.7 SELECTED REFERENCES

(1) "Ti-6Al-2Sn-4Zr-2Mo -- Metallurgical and Mechanical Properties of Ti-6Al-2Sn-4Zr-2Mo Sheet, Bar, and Forgings", Data Sheet from Titanium Metals Corporation of America (September, 1966).

(2) "Ti-6Al-2Sn-4Zr-2Mo -- A New High Temperature Alloy for Service to 1050 F", Data Sheet from Titanium Metals Corporation of America (January 31, 1966).

(3) Personal communications, Titanium Metals Corporation of America (March 30, 1967).

(4) Lane, I. R., Jr., Cavallaro, J. L., and Morton, A. G. S., "Fracture Behavior of Titanium in the Marine Environment", MEL R&D Report 231/65 (Assignment 87 113) (July, 1965).

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1-20 Miscellaneous Titanium Alloys

1-20.0 GENERAL REMARKS

In addition to the coverage of the unalloyed grades and the eight titanium alloys of principal interest in constructing airframes (Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-13V-11Cr-3Al, Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si, Ti-6Al-2Sn-4Zr-2Mo, and Ti-4Al-3Mo-1V), several other compositions have been mentioned as candidates for some application in airframe construction:

Ti-7Al-12Zr
Ti-5Al-5Sn-5Zr
Ti-4Al-0.25O
Ti-2Cu
Ti-7Al-4Mo
Ti-3Al-2.5V
Ti-4Al-4Mo-4V
Ti-1Al-8V-5Fe.

These candidates are not listed in an order of most probable use, but rather in a metallurgical alloy-type order, alpha to beta. Abbreviated information on the candidates designations, potential application, probable use form, and alloy type are given in Table 1-20.0.1. Additional brief sketches of each alloy are given in Sections 1-20.1 to 1-20.8, inclusive.

1-20.1 NOMINAL COMPOSITION AND MAJOR CONSTITUENTS[1,2,3]

Ti-7Al-12Zr

1-20.1.1 Commercial Designations

Ti-7Al-12Zr (Titanium Metals Corporation of America).

1-20.1.2 Alternate Designations

7-12

1-20.1.3 Specifications

MIL-T-9046D, Type II, Composition D.

1-20.1.4 Composition

Constituent	TMCA
Al	6.5-7.5
Zr	11.5-12.5
Fe	0.015 max
C	0.04 max
O	0.10 max
N	0.03 max
H	0.010 max

TABLE 1-20.0.1. OTHER TITANIUM ALLOYS OF POSSIBLE INTEREST FOR AIRFRAME AND ENGINE APPLICATIONS

Nominal Composition, %	Commercial Designations and (Producer)	Potential Application	Most Probable Use Form	Alloy Type	Remarks
Ti-7Al-12Zr	Ti-7Al-12Zr (TMCA)	Fasteners Engine uses	Rod and wire Forgings	Alpha	Weldable
Ti-5Al-5Sn-5Zr	Ti-5Al-5Sn-5Zr (TMCA)	Engine uses	Forgings	Alpha	Weldable
Ti-4Al-0.25O	Ti-4Al-0.25O (TMCA)	Tubing,[a] sheet in secondary structure	Tubes and sheet	Alpha	Weldable
Ti-2Cu	IMI-230 (Imperial Metals Industries, Britain)	Sheet in secondary structure	Sheet	Alpha + compound	Not weldable
Ti-7Al-4Mo	C-15AMo (Crucible) HA-7146 (Harvey) RMI-7Al-4Mo (RMI) Ti-7Al-4Mo (TMCA)	Engine uses, possibly structural airframe parts	Forgings	Alpha beta	Not weldable
Ti-3Al-2.5V	RMI-3Al-2.5V (RMI)	Tubing[a]	Tubes and rod	Alpha beta	Weldable
Ti-4Al-4Mo-4V	Ti-4Al-4Mo (TMCA)	Fasteners	Rod	Alpha beta	Not weldable
Ti-1Al-8V-5Fe	RMI-1Al-8V-5Fe (RMI)	Fasteners	Rod and wire	Metastable beta	Not weldable

(a) Potential tubing uses include airframe structural trusses, ducting, and, possibly, hydraulic lines

1-20.1.5 Alloy Type

Alpha. The Ti-7Al-12Zr composition is an all-alpha-type, since one of the major additions, aluminum, is an alpha stabilizer, while zirconium is a neutral stabilizing addition with complete solubility in alpha titanium. The alloy is not heat treatable, but has moderately high strength at room temperature that is retained to a great extent at elevated temperatures. It has excellent elevated-temperature creep strength, although there is a tendency toward metallurgical instability in some environments. The alloy has excellent weldability.

1-20.1.6 Forms Available

Form	Remarks
Billet	See product availability section for sizes and product details
Bar	
Plate	
Sheet	

1-20.1.7 Description and Metallurgy

The Ti-7Al-12Zr composition was developed as a thick-section forging alloy for elevated-temperature creep-resistant applications. Thus, no beta-stabilizer content is included, which in general lowers elevated-temperature strength. Also, because of the lack of beta-stabilizer addition, the 7-12 can be readily welded without subsequent embrittlement of weld or heat-affected zones due to alpha-precipitation reactions from beta phases. The beta-transus temperature of 7-12 is quite high, and a fairly narrow alpha-beta two-phase region adjoins it. The alloy is nonheat treatable and is usually supplied in the equiaxed alpha-annealed condition.

1-20.2 NOMINAL COMPOSITION AND MAJOR CONSTITUENTS(1,2,3)

Ti 5Al-5Sn-5Zr

1-20.2.1 Commercial Designations

Ti-5Al-5Sn-5Zr (Titanium Metals Corporation of America).

1-20.2.2 Alternate Designations

5-5-5.

1-20.2.3 Specifications

MIL-T-9046D, Type II, Composition C.

1-20.2.4 Composition

Constituent	TMCA
Al	4.5-5.5
Sn	4.3-5.3
Zr	4.7-5.7
Fe	0.15 max
O	0.12 max
C	0.04 max
N	0.03 max
H	0.0150 max for sheet
	0.0125 max for bar
	0.0100 max for billet

1-20.2.5 Alloy Type

Alpha. The Ti-5Al-5Sn-5Zr alloy is an all-alpha type similar to the Ti-7Al-12Zr alloy, except that, since it has lower alloy content, it is less strong. The alloy is noted for its good elevated-temperature strength, stability, and weldability.

1-20.2.6 Forms Available

Form	Remarks
Billet	See product availability section for sizes and product details
Bar	
Plate	
Sheet	
Strip	

1-20.2.7 Description and Metallurgy

The Ti-5Al-5Sn-5Zr composition is less highly alloyed than the Ti-7Al-12Zr alloy. The tin addition is a neutral stabilizer, but is wholly soluble in alpha titanium. The strengthening of 1 percent aluminum is usually equalled by about 3 percent tin. Thus, in the 5-5-5, the aluminum plus tin is about equal to the aluminum in 7-12 on an alpha-phase-strengthening basis. The zirconium content in 5-5-5 is, of course, lower, which results in a lower strength alloy but also one with good metallurgical stability in thermal exposure. The all-alpha nature of the composition permits excellent weldability.

1-20-3 NOMINAL COMPOSITION AND MAJOR CONSTITUENTS(4,5,6)

Ti-4Al-0.25O

1-20.3.1 Commercial Designations

Ti-4Al-0.25O (Titanium Metals Corporation of America).

1-20.3.2 Alternate Designations

Texture-strengthened alloy.

1-20.3.3 Specifications

None.

1-20.3.4 Composition

Constituent	TMCA
Al	3.5-4.5
O	0.2-0.3
Fe	--
C	--
N	--
H	--

1-20.3.5 Alloy Type

Alpha. The Ti-4Al-0.25O alloy is an all-alpha type, since both the major additions, aluminum and oxygen, are alpha stabilizers. Iron, a beta stabilizer, is controlled to low limits to prevent the stabilization of beta phase. The alloy was developed especially for its texture-strengthening capabilities. It has moderately low strength level, but is very formable and weldable.

1-20.3.6 Forms Available

Form	Remarks
Sheet Tubing	See product availability section for sizes and product details

1-20.3.7 Description and Metallurgy

The early experimental work reported by TMCA showed that standard processing practices did not induce a strong anisotropy in the Ti-5Al-2.5Sn or Ti-6Al-4V alloys. The study did show the the alpha alloy was more prone to texturing than the Ti-6Al-4V alloy and that texture strengthening was definitely related to the basal-plane orientation of the hcp structure.

Further work at TMCA has been directed toward tailoring a composition and processing technique to result in a maximum texturing benefit. An alloy containing 4 percent aluminum with a controlled oxygen content (nominally 0.2 to 0.3 percent) was found to be especially suitable for texturing. The aluminum inhibits the rotation of the basal-plane orientation away from the plane of the flat product and also serves to reduce twinning. Twinning would serve as a mechanism to aid thinning in conjunction with slip. Tests on this material at Massachusetts Institute of Technology indicated that the amount of texture hardening in this alloy is large. R was determined to be about 5.1. Experimental points for combined stress loading were obtained from through-thickness compression and plane-strain tests (both tension and compression). TMCA also has shown that the Ti-4Al-O alloy has good notch toughness as low as -423 F.

It is believed that texture strengthening will be especially useful in improving material for cryogenic-pressure-vessel applications. While not limited to this usage, the strength advantages at the lower temperatures appear attractive.

Investigations are in progress, which are an outgrowth of the work by Backofen, et al, that seek to take advantage of titanium-alloy anisotropy. The theory of interest is known as texture hardening or texture strengthening. While present technology eliminates most sheet anisotropy with regard to rolling direction, short transverse (normal) anisotropy is present in some titanium products. This is observed as a resistance to straining through the thickness of the sheet and results from the preferred orientation of the principal slip system. The <11$\bar{2}$0> slip directions are oriented parallel to the plane of the sheet and are thus not available for slip through the sheet thickness. In biaxially loaded sheet, which cannot contract freely in either the length or width direction, deformation occurs more by thinning than in uniaxially loaded sheet. The net result, in material resistant to thinning, is an increase in strength. Increases in yield strength as high as 60 percent have been predicted for titanium sheet properly textured.

1-20.4 NOMINAL COMPOSITION AND MAJOR CONSTITUENTS[7,8]

Ti-2Cu

1-20.4.1 Commercial Designations

IMI 230 (Imperial Metals Industries, Division of Imperial Chemical Industries, Britain).

1-20.4.2 Alternate Designations

None.

1-20.4.3 Specifications

None.

1-20.4.4 Composition

Constituent	IMI-ICI
Cu	2.0
Fe	Maximums permitted are unknown
C	Maximums permitted are unknown
O	Maximums permitted are unknown
N	Maximums permitted are unknown
H	Maximums permitted are unknown

1-20.4.5 Alloy Type

Alpha-Compound. The Ti-2Cu alloy is a binary alloy of low alloy content that offers few advantages over unalloyed titanium. The chief advantage is a slight increase in elevated-temperature strength. However, the advantage is only realized up to about 500 F, at which temperature overaging (the agglomeration of compound [Ti_2Cu] from alpha) can occur in prolonged exposure. Welding is not recommended since this compound can precipitate during fusion, resulting in embrittlement.

1-20.4.6 Forms Available

Form	Remarks
All forms are probably available, since the alloy is fabricated with comparative ease	No details are available

1-20.4.7 Description and Metallurgy

Copper is soluble in alpha titanium up to about 2 percent at 1470 F. The Ti-Cu system is eutectic with eutectoidal decomposition of beta phase at 1470 F to form alpha plus intermetallic compound, Ti_2Cu. The solubility of copper decreases below 1470 F to about 0.5 percent at near room temperature. Thus, the Ti-2Cu alloy is normally used in the annealed alpha plus compound structural condition. Aging of this structure results in further compound precipitation and consequently slight strengthening. The advantage of the Ti-2Cu alloy over unalloyed titanium strengthened with interstitials is that interstitial elements lose their strengthening effect at elevated temperatures, whereas the dispersed-phase (Ti_2Cu) strengthened alloy does not. The chief disadvantage with the dispersed-phase alloy is the embrittlement that can occur during welding operations. Thus the Ti-2Cu alloy is not recommended for welded applications.

1-20.5 NOMINAL COMPOSITION AND MAJOR CONSTITUENTS(3,9)

Ti-7Al-4Mo

1-20.5.1 Commercial Designations

C-135A Mo (Crucible Steel Company)
HA-7146 (Harvey Aluminum Company)
RMI-7Al-4Mo (Reactive Metals, Inc.)
Ti-7Al-4Mo (Titanium Metals Corporation of America).

1-20.5.2 Alternate Designations

Ti-7-4 or 7-4.

1-20.5.3 Specifications

MIL-T-9046, Type III, Composition F.

1-20.5.4 Composition

Constituent	RMI and TMCA
Al	6.5-7.3
Mo	3.4-4.5
Fe	0.25 max
C	0.08 max
O	--
N	0.05 max
H	0.0125 max for bar 0.0100 max for billet

1-20.5.5 Alloy Type

Alpha-Beta. The Ti-7Al-4Mo alloy is an alpha-beta alloy type. It is used principally as a forging alloy. From the solution-heat-treated condition it is age hardenable to high-strength levels. It is a higher strength-level alloy than the familiar Ti-6Al-4V alloy, although at the higher strength levels it has poorer fracture toughness. The alloy may be used in the aged condition to temperatures up to 850 F. Up to this temperature, in the fulled aged condition the alloy is stable. Welding is not recommended.

1-20.5.6 Forms Available

Form	Remarks
Billet Bar Plate Wire Extrusions	See product availability section for sizes and product details

1-20.5.7 Description and Metallurgy

The Ti-7Al-4Mo alloy is a heat-treatable alpha-beta alloy that contains an alpha stabilizer (aluminum) and a beta stabilizer (molybdenum). The aluminum addition increases the temperature limit of the alpha-beta field, thereby extending the hot-working range, and strengthens the alpha phase both at room and elevated temperatures by solid-solution strengthening.

The molybdenum addition, in stabilizing the beta phase, renders the alloy heat treatable, and strengthens the beta phase by solid-solution strengthening. The Ti-7Al-4Mo alloy has more beta phase in the annealed microstructure than does the Ti-6Al-4V alloy because of the much lower solubility of molybdenum in alpha. Also, since molybdenum forms an isomorphous system with titanium, the alloy is not subject to thermal instability caused by eutectoid decomposition.

The Ti-7Al-4Mo alloy may be used in either the annealed or the aged condition. Solution heat

treatment of the metal prior to aging heat treatment is required. The recommended annealing treatment for the Ti-7Al-4Mo alloy is 1 hour at 1450 F, furnace cool to about 1050 F, then air cool to room temperature. Solution heat treatment may be carried out at temperatures between 1600 and 1800 F, although 1700 to 1750 F is recommended. Solution times range between 1/2 and 1-1/2 hours, and the treatment is terminated by water quenching. Aging treatments can be between 950 and 1150 F for times up to 24 hours. Typical aging treatments are for 4 to 8-hour exposure at about 1050 F.

The elevated-temperature stability of this alloy is fairly good if (1) annealing treatments include sufficient annealing exposure and sufficient slow clooling to the stabilization temperature or (2) the aging treatment is optimumly selected for sufficient aging for high strength and aging temperature is just above the proposed service temperature.

1-20.6 NOMINAL COMPOSITION AND MAJOR CONSTITUENTS[10,11]

Ti-3Al-2.5V

1-20.6.1 Commercial Designations

RMI-3Al-2.5V (Reactive Metals, Inc.).

1-20.6.2 Alternate Designations

3 - 2-1/2 tubing alloy
Half 6-4 alloy

1-20.6.3 Specifications

None.

1-20.6.4 Composition

Constituent	RMI
Al	2.5-3.5
V	2.0-3.0
Fe	--
C	--
O	--
N	--
H	--

1-20.6.5 Alloy Type

Alpha-Beta (Lean Beta). The Ti-3Al-2.5V alloy is a lightly alloyed composition of the alpha-beta type, developed especially for welded and seamless tubing aplication. It has greater room and elevated-temperature strength, greater flarability, and lower density than middle-strength grades of unalloyed titanium. Further, it is capable of age hardening to moderate strength levels that are appreciably higher than those of unalloyed titanium.

1-20.6.6 Forms Available

Form	Remarks
Tubing	See product availability
Sheet	section for sizes and
Bar	product details

1-20.6.7 Description and Metallurgy

The Ti-3Al-2.5V alloy is a true alpha-beta type, although the composition has a very lean beta content. In fact, the vanadium is quite soluble in the alpha phase and augments the aluminum addition in strengthening that phase. The low total alloy content does not afford much strengthening potential from the solution-heat-treating and aging processes. However, because of the presence of a beta stabilizer, some age hardenability is present, and, in addition, the beta permits good formability. Because the beta content is low, the grade may be welded without subsequent embrittlement.

1-20.7 NOMINAL COMPOSITION AND MAJOR CONSTITUENTS[12]

Ti-4Al-4Mo-4V

1-20.7.1 Commercial Designations

Ti-4Al-4Mo-4V (Titanium Metals Corporation tion of America).

1-20.7.2 Alternate Designations

4-4-4.

1-20.7.3 Specifications

None.

1-20.7.4 Composition

Constituent	TMCA
Al	3.5-4.5
Mo	3.5-4.5
V	3.5-4.5
Fe	--
O	--
C	--
N	--
H	--

1-20.7.5 Alloy Type

Alpha-Beta. The Ti-4Al-4Mo-4V composition is an alpha-beta alloy developed for thick-section forgings and fasteners. Because of a rich beta stabilizer content, the alloy has deep hardenability and can be strengthened to high levels by aging treatments. Also, because of the high beta stabilizer content, welding is not recommended.

1-20.7.6 Forms Available

Form	Remarks
Billet	See product availability section for sizes and product details
Bar	
Rod	
Wire	

1-20.7.7 Description and Metallurgy

Since this composition has only recently been considered for aircraft-fastener usage, not much information on the metallurgy of the composition has been published. The beta-stabilizer alloy content is quite high, and therefore one can assume that it might behave metallurgically like Ti-16V-2.5Al or Ti-6Al-6V-2Sn alloys. Similarly, it should be somewhat like Ti-4Al-3Mo-1V alloy but with richer beta content, a lower beta transus, a more stable beta phase, and a greater age-hardening response. Also, because of the higher beta content, the 4-4-4 is less weldable than 4-3-1.

1-20.8 NOMINAL COMPOSITION AND MAJOR CONSTITUENTS(13,14)

Ti-1Al-8V-5Fe

1-20.8.1 Commercial Designations

RMI-1Al-8V-5Fe (Reactive Metals, Inc.).

1-20.8.2 Alternate Designations

1-8-5
185 beta alloy
RMI-185.

2-20.8.3 Specifications

None.

1-20.8.4 Composition

Constituent	RMI
V	7.5-8.5
Fe	4.5-5.5
Al	0.8-1.8
C	0.05 max
O	0.3-0.5
N	0.07 max
H	0.0125 max

1-20.8.5 Alloy Type

Metastable Beta. The Ti-1Al-8V-5Fe alloy can be quenched to the all-beta structure because of high beta-stabilizer content. Because of the relative instability of iron-stabilized beta, the beta structure also can be readily decomposed to precipitate alpha and compound phases. The decomposition of the beta phase by aging treatments results in very high strength levels. The alloy is not weldable because of problems of embrittlement after welding.

1-20.8.6 Forms Available

Form	Remarks
Billet	See product availability section for sizes and product details
Bar	
Rod	
Plate	

1-20.8.7 Description and Metallurgy

The Ti-1Al-8V-5Fe alloy is a high-strength, heat-treatable composition capable of developing strengths over 200 ksi. This high strength, coupled with good ductility and other good properties in small section sizes make it attractive for fastener applications. Material is usually supplied in the annealed condition.

1-20.20 REFERENCES

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SECTION 2

Product Availability

2-0 Sources and Nomenclature for Titanium Alloys[1,2]

2-0.0 GENERAL REMARKS

Titanium metal stock is available from several companies. Some of these companies have complete facilities to process stock through all the steps from ore to mill product, while others specialize in a single product form. Each of the companies describes its products under distinctive nomenclature, and most companies offer a variety of titanium alloys for various end uses.

2-0.1 TITANIUM PRODUCERS

The principal titanium-product companies are:

Crucible Steel Company of America (Crucible)
Harvey Aluminum Company (Harvey)
Oregon Metallurgical Corporation (Oremet)
Reactive Metals, Incorporated (RMI)
Titanium Metals Corporation of America (TMCA).

Oremet, RMI, and TMCA are domestic producers of titanium metal (sponge form). The other companies purchase metal (sponge) from the domestic producers or from importers of Japanese or British sponge titanium. The base metal is melted by the producers, either alone or with alloying ingredients, to form ingots. Ingots in turn are processed to mill shapes or are converted to forged and extruded shapes for additional processing and/or subsequent use.

Currently, the capacity of United States producers to produce sponge titanium is at the level of about 32 million pounds per year. All domestic producers have active programs to increase this capacity. Domestic titanium sponge consumption is greater than sponge production, and the difference is made up of foreign-produced import sponge. In 1966, imports totaled about 10 million pounds.

Since the annual growth rate for titanium mill products has been increasing rapidly over the last few years, it is obvious that the expanding capacity to produce sponge is a basic requirement for the continued growth of the industry.

2-0.2 PRODUCT NOMENCLATURE

Alloy designations vary according to the individual producer. The nomenclature used for identifying alloyed and unalloyed titanium is presented in Table 2-0.2-1.

2-0.3 SUPPLY SOURCES FOR METAL FORMS AND SHAPES

While a variety of unalloyed titanium grades and titanium alloys are offered by the five major producers, only a few are of prime consideration in the planning of advanced aircraft. The mill products available in these specific materials are not all standard shelf items and are not common to each company. In addition to the five major producers, numerous other sources of mill products and fabricated forms exist. These are called out, on the basis of existing information, in the sections that follow. Obviously, the number of these secondary supply sources is continually changing. Hence, the lists should not be considered final or complete.

TABLE 2-0.2-1. PRODUCT NOMENCLATURE USED BY MAJOR TITANIUM PRODUCERS

Nominal Composition %	Alloy Designations According to Supplier				
	Crucible	Harvey	Ore-met	RMI	TMCA
99.5Ti	A-30	HA-1930	(a)	RMI-30	Ti-35A
99.2Ti	A-40	HA-1940	(a)	RMI-40	Ti-55A
99.0Ti	A-55	HA-1950	(a)	RMI-50 RMI-55	Ti-65A
99.0Ti	A-70	HA-1970	(a)	RMI-70	Ti-75A Ti-100A
Ti-0.15 to 0.2Pd	A-40Pd	HA-1940Pd	(a)	RMI-0.2Pd	Ti-0.15Pd
Ti-5Al-2.5Sn	A-110AT	HA-5137	(a)	RMI-5Al-2.5Sn	Ti-5Al-2.5Sn
Ti-5Al-2.5Sn (low 0)	A95AT	HA-5137 ELI	(a)	RMI-5Al-2.5Sn ELI	Ti-5Al-2.5Sn ELI
Ti-5Al-5Sn-5Zr	--	--	-	--	Ti-5Al-5Sn-5Zr
Ti-7Al-12Zr	--	--	-	--	Ti-7Al-12Zr
Ti-7Al-2Cb-1Ta	--	--	-	RMI-7Al-2Cb-1Ta	Ti-7Al-2Cb-1Ta
Ti-6Al-2Cb-1Ta-0.8Mo	--	--	-	RMI-6Al-2Cb-1Ta-0.8Mo	--
Ti-6Al-2Sn-4Zr-2Mo	--	--	-	RMI-6Al-2Sn-4Zr-2Mo	Ti-6Al-2Sn-4Zr-2Mo
Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si	--	--	-	--	Ti-679
Ti-8Al-1Mo-1V	--	HA-8116	(a)	RMI-8Al-1Mo-1V	Ti-8Al-1Mo-1V
Ti-8Mn	C-110M	--	-	RMI-8Mn	Ti-8Mn
Ti-2Fe-2Cr-2Mo	--	--	-	--	Ti-140A
Ti-2.5Al-16V	--	--	-	RMI-16V-2.5Al	--
Ti-3Al-2.5V	--	--	-	RMI-3Al-2.5V	--
Ti-4Al-4Mn	C-130AM	HA-4145	-	RMI-4Al-4Mn	--
Ti-4Al-3Mo-1V	--	--	-	RMI-4Al-3Mo-1V	Ti-4Al-3Mo-1V
Ti-4Al-4Mo-4V	--	--	-	--	Ti-4Al-4Mo-4V
Ti-5Al-4FeCr	--	--	-	--	Ti-5Al-4FeCr
Ti-5Al-4FeCrMo	--	--	-	--	Ti-155A
Ti-6Al-4V	C-120AV	HA-6510	(a)	RMI-6Al-4V	Ti-6Al-4V
Ti-6Al-4V (low 0)	C-120AV	HA-6510 ELI HA-6148	(a)	RMI-6Al-4V ELI	Ti-6Al-4V ELI
Ti-6Al-6V-2Sn	C-125AVT	HA-5158	(a)	RMI-6Al-6V-2Sn	Ti-6Al-6V-2Sn
Ti-7Al-4Mo	C-135AMo	HA-7146	(a)	RMI-7Al-4Mo	Ti-7Al-4Mo
Ti-1Al-8V-5Fe	--	--	-	RMI-1Al-8V-5Fe	--
Ti-3Al-13V-11Cr	B-120VCA	--	-	RMI-13V-11Cr-3Al	Ti-13V-11Cr-3Al

(a) Oremet offers ingots and/or selected mill products of these alloys without specific nomenclature.

2-1 Ingot Production and Capabilities

2-1.0 GENERAL REMARKS

All of the principal producers cast ingot for subsequent conversion to mill products. Lately, other companies who are now concerned only with fabrication of titanium products have acquired or have expressed interest in acquiring melting equipment. For example, a major forger of large titanium shapes is considering installation of melting equipment.

The ingot-producing capabilities of the five principal melters of titanium are given in Table 2-1.0.1. Table 2-1.0.2 shows the current availability of selected titanium alloy ingots among these five sources.

TABLE 2-1.0.1. PRODUCTION CAPABILITIES FOR TITANIUM INGOT

	Maximum Ingot Size		Typical Large Ingot	
Producer	Diameter, in.	Weight, lb	Diameter, in.	Weight, lb
Crucible Steel	32	9,500	32	9,500
Harvey Aluminum	23-27	4,400	20	4,000
Oremet	20	3,500	20	3,500
Reactive Metals	36 48(a)	15,000 38,000(a)	30	9,500
TMCA	32 (44-45)(a)	11,600 (17,000-25,000)(a)	28-30	NA

(a) Sizes contemplated.

TABLE 2-1.0-2. PRODUCER SOURCES FOR SELECTED TITANIUM-ALLOY INGOTS

Nominal Composition, %	Crucible	Harvey	Oremet	RMI	TMCA
Commercially Pure Ti	x	x	x	x	x
Ti-5Al-2.5Sn	x	x	x	x	x
Ti-8Al-1Mo-1V	--	x	x	x	x
Ti-6Al-4V	x	x	x	x	x
Ti-13V-11Cr-3Al	x	--	x	x	x
Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si	--	--	--	--	x
Ti-6Al-2Sn-4Zr-2Mo	--	--	--	x	x
Ti-4Al-3Mo-1V	x	--	--	x	x

2-2 Forgings[1]

2-2.0 GENERAL REMARKS

Each of the major titanium producers has forging capacity and capability but does not engage in the forging business per se. A producer's forging activities are generally confined to ingot forging to provide billet material for sale to forge companies. Forge billets generally have a cross-sectional area of 16 square inches or more and are available in rounds, squares, rectangles, and octagons. Many forging companies have extensive experience in forging titanium. Typical of these and representing a wide range of forging capacity, are the companies listed below:

- Alcoa, Cleveland, Ohio
- Arcturus Manufacturing Corporation, Oxnard, California
- Berkeley Forge & Tool Company, Berkeley, California
- California Drop Forge Company, Los Angeles, California
- Cameron Iron Works, Houston, Texas
- Carlton Forge Works, Paramount, California
- Consolidated Industries, Cheshire, Connecticut
- Coulter Steel & Forge Company, Emeryville, California
- Kropp Forge Company, Chicago, Illinois
- Ladish Company, Cudahy, Wisconsin
- Ladish Pacific, Los Angeles, California
- Ontario Corporation, Muncie, Indiana
- Pacific Forge, Incorporated, Fontana, California
- Park Drop Forge Company, Cleveland, Ohio
- Precision Forge Company, Santa Monica, California
- Reisner Metals, Incorporated, South Gate, California
- Standard Steel, Division of BLH, Burnham, Pennsylvania
- Steel Improvement and Forge Company, Cleveland, Ohio
- Storms Drop Forge Company, Springfield, Massachusetts
- Taylor Forge and Pipe Works, Chicago, Illinois
- TRW Incorporated, Cleveland, Ohio
- Valley Forge Company, Azusa, California
- Viking Forge & Steel Company, Albany, California
- West Coast Forge, Incorporated, Compton, California
- Wyman-Gordon Company, Worcester, Massachusetts.

It should be noted that other forging companies are continually entering the titanium-forging field and that this listing should not be considered complete.

The largest forging equipment in service at present includes:

Two 50,000-ton hydraulic presses (Alcoa and Wyman-Gordon)
One 125,000-meter-kilogram counterblow hammer (Ladish Company).

These forging units are considered to represent similar plan-area capacity for disks and structural parts up to about 11 feet in length. Because they have longer platens, the presses are capable of forging slender forgings up to 22 feet in length, consistent with the maximum plan areas for the alloy being forged.

The maximum plan areas that can be forged on the 50,000-ton presses are compared below for titanium and aluminum.[3]

Design Type	Maximum Plan Area on 50,000-Ton Press, in.^{2}	
	Al	Ti Alloys
Blocker	5,000	2,000
Finish	2,500	1,400

Plan areas of 1200 in.^{2} are now common for titanium parts and require almost full press capacity. Forged parts 5 feet in diameter and weighing up to 1500 pounds can be made in production quantities. It should be noted that certain generously contoured parts as large as 4000 in.^{2} could be forged on this larger equipment, provided the shape is somewhat symmetrical and the ribs and other projections are fairly shallow. The individual forging companies are in the best position to determine the size limitations on a part basis.

2-2.1 CLASSIFICATION OF TITANIUM DIE FORGINGS BY SHAPE AND DESIGN TOLERANCES

Configurations of titanium forgings can be classified broadly as follows: (1) rib-and-web structural shapes, (2) forged rings, (3) disk shapes. Certain of these general shapes lend themselves to higher degrees of dimensional precision than do others during forging. It should be pointed out that there is a problem of semantics in classifying forgings by tolerance groups. For example, one forging company might consider "close-tolerance forgings" as forgings that have (1) shallower than normal draft angles, (2) smaller than normal fillet radii, and (3) closer than normal tolerances for die wear, shrinkage, mismatch, etc. Another forging company might interpret "close-tolerance forgings" as "no-draft forgings" that require only a slight amount of spot facing or drilling before being placed into service. Both companies would probably be right in their interpretation, but a more definite line of demarcation between the design types is needed.

Titanium forgings are classified into four distinct tolerance groups: (1) blocker-type tolerances, (2) conventional tolerances, (3) close tolerances, and (4) precision tolerances. Detailed production tolerances for forging titanium alloys are provided in Table 2-2.1-1. These data are typical of industry capabilities.[4,5] Examples of the types of forging shapes commonly produced and their availability in the several categories of dimensional tolerances is provided in Table 2-2.1-2.[5]

2-2.1.1 Blocker-Type Design

Blocker-tolerance forgings are usually produced from one set of dies and conform to the general shape of the final part. Adequate machining stock is present so that surface defects may be removed. The design usually allows for adequate metal flow so that the resulting metallurgical properties are comparable to those found in forgings of conventional design. In blocker-type designs, very little attention is paid to die wear, die shift, fillet radii, draft angles, die closure, and other tolerances described by the ASM Committee on Forgings.

2-2.1.2 Conventional-Tolerance Designs

The ASM Committee's description of commercial tolerances applies to the conventional design. Some of the forging companies offer closer tolerances than these in order to reduce metal requirements. In these instances, the general design remains conventional, but machining allowances and die-closure tolerances are reduced to effect a weight saving.

2-2.1.3 Close-Tolerance Designs

Compared with conventional designs, close-tolerance forging designs require greater dimensional accuracy and less draft. Less machining cleanup is allowed and, in some cases, localized "as forged" surfaces are specified. Additional tooling is usually required for forging, but the parts are forged in conventional equipment and conventional tooling.

2-2.1.4 Precision-Tolerance Designs

Precision forgings are those that require both special tooling and forging equipment. This type of forging usually combines very close tolerances with small fillets and radii, no draft, and little or no machining allowances. The special equipment usually consists of slow-rate presses or specially developed impactors. The complex tooling required might consist of split dies, segmented dies, or dies that can be heated to temperatures approaching the forging temperature. Even preliminary tooling must have a high degree of accuracy so that the volume of stock in the forging does not vary from part to part. To achieve this accuracy, complex additional tooling is usually required. In titanium alloys, precision-tolerance forgings are available only in limited size and shape, as indicated in Table 2-2.1-2. It should be noted that precision-tolerance designs are produced on a "best efforts" basis by only two or

TABLE 2-2.1-2. AVAILABILITY OF SPECIFIC TOLERANCES FOR EACH OF SEVERAL FORGING SHAPES IN TITANIUM ALLOYS[5](a)

Forgings classified by dimensional tolerance

Forged Shape	Blocker-Type Tolerances	Conventional Tolerances	Close Tolerances	Precision Tolerances
Disks	A	A	L	U
Cones	A	A	L	U
Hemispheres	A	A	L	U
Cylinders	A	A	L	U
Blades	A	A	A	L
Airframe (fittings)	A	A	A	LS
Airframe (rib and web)	A	A	L	U
Rings	A	A	L	U

(a)Code: A = Readily available
L = Limited availability
LS = Limited availability - small parts only
U = Virtually unavailable.

TABLE 2-2.1-1. GENERAL FORGING TOLERANCES FOR TITANIUM ALLOYS[4,5]

	Blocker Forgings			Conventional Forgings			Close-Tolerance Forgings		Precision Forgings(a)
Design Criteria	Large(b)	Medium(c)	Small(d)	Large	Medium	Small	Medium	Small	Small
Min Draft Angle, deg	5-7	5	5	5	5	3-5	3-5	3	0-1
Min Web Thickness, in.	0.75-1.00	0.62-0.75	0.62	0.62-0.75	0.50-0.62	0.25-0.38	0.25-0.31	0.20	0.15
Min Rib Width, in.	0.88-1.25	0.75-1.00	0.62-0.75	0.62-0.75	0.50-0.62	0.31-0.50	0.25-0.38	0.19-0.25	0.09
Min Corner Radius, in.	0.44	0.38	0.31-0.38	0.31	0.25-0.31	0.16-0.25	0.12-0.19	0.12	0.06
Min Fillet Radius, in.	1.00-2.00	1.00-2.00	0.88-1.50	1.00-1.50	0.88-1.00	0.75-0.88	0.38	0.25	0.12-0.19
Die Wear, surface in.	0.25	0.19	0.12	0.12	0.12	0.09	0.06	0.03	0.01-0.03
Thickness Tolerance, in.	+0.38 -0.03	+0.23 -0.03	+0.35 -0.03	+0.25 -0.03	+0.12 -0.03	+0.09 -0.03	+0.06 -0.03	+0.04 -0.01	+0.02 -0.01
Length and Width, in./ft	±0.03	±0.03	±0.03	±0.03	±0.03	±0.03	±0.03	±0.03	±0.02
Straightness Tolerance, Within, in.	0.25	0.25	0.19	0.19	0.09	0.06	0.03	0.03	0.02
Machining Coverage, in. max	0.38	0.31	0.25	0.25	0.12	0.09	0.03	0.00-0.03	0.00-0.03

(a) The experience and capability with respect to precision-type forgings is very limited. No parts are being produced on a production basis at present. Values shown are based on available data and are aim values considered reasonable once techniques are developed for producing this type product.

(b) Large: larger than 400 in.^{2}.

(c) Medium: 100 to 400 in.^{2}.

(d) Small: less than 100 in.^{2}.

three suppliers. Tolerances listed in Table 2-2.1-1 should, therefore, be considered as "aims" and negotiated with the suppliers.

2-2.1.5 Rolled Rings

Rolled-ring forgings from titanium are produced in sizes up to about 5 inches in diameter with lengths (or face heights) of up to 48 inches, and wall thicknesses of about 3/4 inch. The manufacturing limit on diameter and length are 260 inches and about 55 inches, respectively. For reasons related to billet availability, the larger diameter rings would have proportionately shorter lengths and vice versa.

Rings of smaller sizes can be rolled with either inside or outside contours or both. Specially contoured drive rolls or mandrel rolls are necessary to achieve the desired ring contours. For this reason, contour-rolled rings are suggested only when the weight savings offset the added tooling costs. Forging vendors should be consulted for optimum ring design.

Most of the forging producers listed in 2-2.0 are capable of forging ring shapes. The larger size rings- namely, 12 inches or longer and having diameters over 4 feet- are produced by fewer companies. Among these are:

- Cameron Iron Works, Houston, Texas
- Ladish Company, Cudahy, Wisconsin
- Standard Steel, Division of BLH, Burnham, Pennsylvania
- Viking Forge and Steel Company, Albany California.

It should be noted that this list is not complete. Since many of the companies are in the process of installing ring-rolling equipment of various sizes, it is a good practice to include the others at an inquiry stage.

There are no known industry-accepted standards for rolled rings. Dimensional tolerances, finish allowances, and overall dimensions are, therefore, the subject of negotiation between purchaser and vendor.

2-3 Flat-Rolled Products[1]

2-3.0 GENERAL REMARKS

Plate, sheet, and strip products constitute a large share of the current titanium mill-product market. These flat-rolled forms are available in many alloy grades (some titanium alloys are not produced in flat-rolled forms) and are available from several producers.

2-3.1 PLATE

Plate is generally defined as flat-rolled or forged material 0.1875 inch or more in thickness, over 10 inches in width, and having a width greater than 5 times its thickness. Plate is available in unalloyed and alloy titanium in widths up to a maximum of 150 inches (maximum produced to date). Lengths and thicknesses made to this maximum width depend on ingot or billet size and upon product yield. Lengths up to 600 inches and thicknesses up to 6 inches have been produced. While some surface-finishing problems remain to be worked out, the availability of titanium-alloy plate appears to be adequate to meet the demands of aerospace users.

The more common alloy plate sizes produced to date are listed below:

Thickness, in.	Width x Length, in.
0.1875-0.249	100 x 420
0.250-0.374	110 x 420
0.375-0.499	120 x 450
0.500-0.749	130 x 480
0.750-0.999	140 x (a)
1.0 and up	145 x (a)

(a) Any practical length within ingot limitations.

The availability of selected titanium-alloy plate from four producer sources (Harvey Aluminum and Oremet do not make flat-rolled products) is shown in Table 2-3.1-1. The thickness and flatness tolerances of the rolled-plate currently produced are given in Table 2-3.1-2.

2-3.2 SHEET AND STRIP

Flat-rolled titanium mill products are priced as sheet when they are 24 inches or greater in width and less than 0.1875 inch in thickness. The material is priced as strip when it is less than 24 inches in width.

Table 2-3.2-1 shows the "ability to supply" sheet and strip by the major flat-rolled-product producers. Any of the sheet sizes that can be produced in coil can be slit into strip of any desired width.

Table 2-3.1-1 lists current producer sources for sheet and strip of selected titanium alloys. Forty-eight-inch-wide sheet is available in unalloyed titanium grades in thicknesses down to 0.010 inch. In alloy grades, some 0.020-inch-thick sheet is produced in the 48-inch widths. However, this width is more readily available in the heavier gages of 0.032 to 0.187 inch. Alloy sheet 36 inches wide is much more common. In this width, thicknesses down to 0.016 inch are available in selected alloys (Ti-5Al-2.5Sn, for example). For some alloys, 0.020 to 0.030-inch thickness would be a more practical limit at the 36-inch width. Gages thinner than 0.016 inch in alloy sheet are available in widths of 30 inches and less. The difficulty of producing wide sheets in the thinner gages causes one of the present restrictions on size availability of flat-rolled mill products.

Strip of commercially pure grades is available in coils or cut lengths in the full thickness range from about 0.010 inch up. In narrow widths, unalloyed grades are available to even thinner gages. Foil gages can be supplied by reroll facilities.

TABLE 2-3.1-1. PRODUCER SOURCES FOR FLAT-ROLLED PRODUCTS OF SELECTED TITANIUM ALLOYS

Nominal Composition, %	Sources and Available Forms[a]			
	Carlson[b]	Crucible	RMI	TMCA
Commercially Pure Ti	P	P,S,s	P,S,s	P,S,s
Ti-5Al-2.5Sn	--	P	P,S,s	P,S,s
Ti-8Al-1Mo-1V	--	--	P,S	P,S
Ti-6Al-4V	P	P	P,S	P,S
Ti-6Al-6V-2Sn	--	P	P,S	P,S
Ti-13V-11Cr-3Al	--	P	P,S,s	P,S,s
Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si	--	--	--	P
Ti-6Al-2Sn-4Zr-2Mo	--	--	--	P,S
Ti-4Al-3Mo-1V	--	P,S,s	P,S,s	P,S,s

(a) P = plate, S = sheet, and s = strip. Strip is in coils produced on a continuous basis.
(b) G. O. Carlson produces plate from ingot supplied by Crucible.

TABLE 2-3.1-2. TYPICAL THICKNESS AND FLATNESS TOLERANCES OF CURRENT TITANIUM PLATE

Plate Thickness, in	Thickness Tolerance, in.		Variation from Flat Surface, in.	
	Width	Thickness Overage	Width	Variation in 15 Ft
0.1875 to 0.375	Max available	0.050	Up to 48	0.75
0.375 to 1.00	Max available	0.060	Up to 48	0.50
			48 to 76	0.62
1.00 to 2.00	Max available	0.070	Up to 48	0.5 to 0.2[a]
			48 to 76	0.6 to 0.3[a]

(a) Flatness increases with increasing thickness and decreases with increasing plate size.

TABLE 2-3.2-1. AVAILABILITY OF TITANIUM-ALLOY SHEET AND STRIP[a,b]

Thickness, in.	Maximum Width, in.	Maximum Length, in.
0.008-0.012	26	Coil
0.012-0.016	30	Coil
0.016-0.020	36	Coil
0.020-0.032	44	Coil
	48	120-144
0.032-0.060	44	Coil
	48	144
0.060-0.187	48	144

(a) Unalloyed grades are generally available in greater widths at thinner gages than alloy grades.
(b) Tolerances for all gages meet AMS 2242 specifications.

2-4 Bar, Rod, and Wire[1]

2-4.0 GENERAL REMARKS

Rod and bar are available in rounds, squares, and rectangles. Rolled bar, which has a cross-sectional area ranging from 16 square inches down to about 1.4 square inches, has a length restriction because of annealing-furnace limitations. Lengths up to 90 feet are possible, but the usual lengths produced are 16 to 20 feet.

Round bars having diameters less than 0.3125 inch are priced as wire, with lengths greater than 30 feet being available. Small-diameter wire is usually available in coils in lengths between 300 and 500 feet. In general, alloy wire in the smaller sizes is more difficult to obtain than unalloyed wire. Table 2-4.0-1 shows the availability of bar, rod, and wire from the major producers and conversion companies.

Weld filler wire suppliers include the titanium producers (Crucible Steel Company, Harvey Aluminum Company, and Titanium Metals Corporation of America) and three companies who convert bar and wire to wire suitable for weld filler material. These latter companies are Armetco Incorporated, Wooster, Ohio, Astro Metallurgical Company, Wooster, Ohio, and R&D Metals Corporation, Kidron, Ohio (near Wooster). Table 2-4.0-2 presents some information on the availability and sources of titanium weld-filler wire compositions.

TABLE 2-4.0.1. AVAILABLE TITANIUM BAR, ROD, AND WIRE

Cross-Sectional Dimensions, in.				Maximum
Diameter, rounds	Side Squares	Rectangles, X by Y	Hexagonal, diagonal	Length, ft
0.009 to 0.3125(a)	--	--	--	300 to 500
5/16 to 4-1/2	5/16 to 4-1/2	3/16 to 3-1/2 by 1/2 to 10	5/16 to 4-1/2	40 to 50 in smaller sizes, up to 30 in large sizes; 16 to 20 is normal

(a) Wire above 0.3125 inch in diameter is priced as rod.

TABLE 2-4.0-2. AVAILABILITY AND SOURCES OF TITANIUM WELD-FILLER WIRE COMPOSITIONS

Nominal Composition, %	Armetco	Astro-Met	Crucible	Harvey	R&D	TMCA
Unalloyed grades	x	x	x	x	x	x
Ti-0.2Pd	--	--	--	--	--	x
Ti-5Al-2.5Sn	x	--	x	--	--	--
Ti-5Al-2.5Sn (ELI)(a)	--	x	--	--	x	--
Ti-7Al-2Cb-1Ta	--		--	--	x	--
Ti-8Al-1Mo-1V	x	x	--	x	x	x
Ti-6Al-4V	x	x	--	x	--	x
Ti-6Al-4V (ELI)(a)	x	x	--	--	x	x
Ti-6Al-6V-2Sn	x	--	--	--	--	x
Ti-6Al-6V-2Sn (ELI)(a)	--	--	--	--	x	--
Ti-7Al-4Mo	--	--	--	--	--	x
Ti-1Al-8V-5Fe	x	--	--	--	--	--
Ti-13V-11Cr-3Al	x	x	--	--	x	x
Ti-13V-11Cr-3Al (ELI)(a)	x	--	--	--	--	--

(a) Low-oxygen-content grade.

2-5 Extruded Shapes[1]

2-5.0 GENERAL REMARKS

Extrusions were first used in aircraft engines with the advent of the gas turbine--mainly for such parts as nonrotating spacers, rings, and flanges of uniform and usually simple cross section. The extrusions are formed and flash welded into circular shapes to produce these parts.

The use of extruded titanium structural shapes for airframe applications started with the XB-70 aircraft. At the present time, titanium extrusions are being used extensively in three operational military aircraft, including McDonnell's F4 Phantom, North American's A5 Vigilante, and a Mach 3 interceptor. Titanium-alloy extrusions are also being used in the Douglas DC-9 commercial transport, and will be used more extensively in the future in both commercial (Douglas DC-X62, Boeing 737, 747) and military aircraft (F-111, C5A).

In subsonic aircraft, extrusions are being used in critical-load-bearing applications such as wing-fuselage connections, as well as for spars and fuselage bulkhead sections, landing-gear-cover hinges, and a multitude of small applications where additional strength and stiffness is required over what can be obtained with high-strength aluminum alloys. In supersonic aircraft applications, the extensive use of titanium extrusions becomes of paramount importance in meeting the high-stress, elevated-temperature requirements of this type of aircraft.

Extruded shapes are currently supplied in a surprisingly wide variety of configurations, although most of these are basic angle, tee, or channel shapes. Section thicknesses generally vary from 1/8 to 1-1/4 inches within circumscribing circles of 1-1/2 to 11 inches in diameter. Most shapes, however, fit within a 3 to 5-inch-diameter circle.

Extruded lengths supplied currently vary from 20 to 75 feet, with annealed material. For alloys in the solution-treated-and-aged condition, lengths up to 40 feet can be supplied. Longer lengths will be desired once heat-treating facilities become available.

Listed below are the major alloys currently being used as extruded shapes in aircraft applications, in the approximate order of decreasing usage:

Titanium

(1) Ti-6Al-4v
(2) Ti-6Al-6V-2Sn
(3) Ti-5Al-2.5Sn
(4) Ti-8Al-1Mo-1V
(5) Ti-13V-11Cr-3Al.

The Ti-6Al-4V alloy is used in both the annealed and "STA" (solution treated-and-aged) conditions. All other titanium alloys (except the Ti-13V-11Cr-3Al alloy, which also is heat treated) are currently being used in the annealed condition.

Airframe manufacturers require extruded titanium structural shapes of a quality comparable to aluminum extrusions with regard to surface and dimensional tolerance specifications. In the present state of development, as-extruded titanium alloys are not of requisite quality for direct use in airframe applications because of surface contamination and/or surface roughness. As a result, all titanium extrusions are used in the machined condition.

Finish section thicknesses currently being used vary from 0.060 to 0.125 inch. The amount of machining envelope required on an extruded shape varies with the application, part design, etc. Extra envelope may be used to provide for various part configurations. Minimum envelope requirements vary with each company. Some will allow as little as 0.020 inch excess per side, while others require 1/8-inch excess per surface, regardless of part design or application.

The development of extrusion techniques for producing thin-section titanium alloys to aluminum airframe specifications has made some headway. Extrusion studies[6] have demonstrated the ability to produce a tee section to desired specifications by combining extrusion and warm drawing. Alloys investigated were Ti-6Al-4V, Ti-7Al-4Mo, and Ti-4Al-3Mo-1V.

Extrusions in the initial study having a 3/32-inch section thickness were warm drawn in 20-foot lengths to 0.080-inch thickness. Thickness tolerances of ±0.005 inch were met. Flange and leg length tolerances of ±0.005 inch could be met only by edge maching. Straightness requirements of 0.010-inch per foot of length; 1/2 degree per foot, 3 degrees maximum twist; and ±1/2 degree angle, were all realized. Surface finish of the drawn sections was 80 microinch, under the 100-microinch target specifications.

Subsequent studies along these same lines were made on the Ti-13V-11Cr-3Al alloy.[7] Eight full-length (15 to 20 foot) extrusions were made in 1/8-inch, 3/32-inch, and 1/16-inch cross-section thicknesses (extrusion ratios of 30, 50, and 80:1). Severe die wash was encountered, and the alloy was sensitive to attack by the glass lubricants used on other titanium alloys. Thus, additional research remains to develop optimum extrusion techniques for this alloy.

Recent work[8] has further developed extrusion techniques on Ti-6Al-4V and Ti-8Al-1Mo-1V alloy extruded shapes to produce 1/16-inch-thick sections

TABLE 2-5.0-1. TYPICAL MANUFACTURING LIMITS AND TOLERANCES FOR TITANIUM EXTRUSIONS

Manufacturing Limits

Size Limitations

(a) Circumscribing-circle diameter: the diameter of the smallest circle that will completely enclose the cross section of the shape - 2 inch minimum, 21 inch maximum

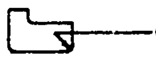
(b) Cross-sectional area - 0.125 square inch, minimum

(c) Length - 75 ft (annealed)
40 ft (STA condition)

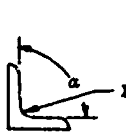
Dimensional Limitations

(a) Section thickness - 0.090 inch minimum, 0.250 inch typical

(b) Corner radii - 0.020 inch minimum, 0.080 inch typical

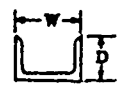

Corner

(c) Fillet radii - 0.125 inch minimum, 0.250 inch typical


Fillet

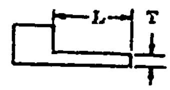
Design Properties

(a) Tongue ratio



W should be equal to or greater than D, $W/D \geq 1$

(b) Leg length-to-thickness ratio



L should not exceed 14 T, $L/T \leq 14$

Tolerances

Cross-Sectional Tolerances

(a) Dimensions, specified length or thickness up to

	Annealed Condition	STA Condition
1 inch	±0.020	±0.030
1-2 inches	±0.020/ 0.030	±0.040
2-3 inches	±0.030/ 0.040	±0.040
3-4 inches	±0.040/ 0.060	±0.060

(b) Corner and fillet radii


Corner ±0.025 inch
Fillet ±0.062 inch

(c) Angles

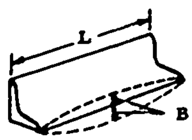

Angle ±2 degrees

(d) Transverse flatness

Allowable, D from flat:
D = 0.010 x W (inches), 0.010 inch minimum

Longitudinal Tolerances

(a) Straightness or bow:



Maximum allowable B in inches = 0.025 inch in 1 foot
0.125 inch in 5 feet

(b) Twist

Maximum allowable T in degrees:
1° per foot of L;
5° maximum

(c) Length:

Tolerance in cutting length = +1/4 inch, -0.00 inch

Surface Finish

(a) Roughness:
Maximum roughness = 250 rms (This value is used as a guide only since rms standards are established primarily for machined surfaces and may not be directly applicable in all respects to extruded surfaces.)

(b) Local defects:
Local defects, such as gouges, dents, handling marks and lineslaps, may extend a maximum of 0.015 inch below the minimum dimensional tolerance.

having thickness tolerances of ±0.005 inch, with surface finishes of 50 to 150 microinches. This study is still underway.

To date, no thin-section titanium-alloy extrusions have been produced on a commercial basis. However, H. M. Harper Company has recently announced the availability of 0.090-inch-thick Ti-6Al-4V extruded shapes that meet commercial tolerances. The eventual commercial production of thin-section shapes may be realized by the combination of extrusion and warm drawing. H. M. Harper is now working in this direction. At present, however, titanium extrusions for aircraft applications require complete surface machining in order to meet the required tolerances.

A current program[9] on the production of integrally stiffened extruded panels of Ti-6Al-4V and Ti-6Al-6V-2Sn alloys has met with initial success in early trials using the 12,000-ton press at Curtiss-Wright. A four-ribbed panel, 16 inches wide with 0.4-inch-thick stiffeners, represents the current target shape, although it is expected that panels 28 inches wide by 65 feet in length will eventually be produced. In the first trials, good die fill was obtained and extrusions were quite straight. This program shows considerable promise in the production of stiffened titanium panels.

Table 2-5.0-1 contains typical standard manufacturing limits and tolerances for titanium extrusions.

A list of current extrusion press capabilities for titanium is presented in Table 2-5.0-2. Harvey Aluminum, TMCA (Allegheny-Ludlum), H. M. Harper, and Curtiss-Wright are currently supplying titanium extrusions to the aircraft industry. Reactive Metals is now modifying their equipment at Ashtabula, Ohio (including a 3,850-ton extrusion press) for the future production of titanium extrusion. TMCA is planning to install a new extrusion press in their Toronto, Ohio, plant.

Canton Drop Forge and Babcock and Wilcox are included in this list because their extrusion facilities are amenable to titanium extrusion production. Neither are active in this area, however, at the present time.

As a substitute for an extruded shape, a rolled shape might be considered. However, the use of rolled shapes would only become practical if sufficient quantities of a given shape are required. The high cost of tooling for this type of forming operation precludes anything except high-production items.

TABLE 2-5.0-2. EXTRUSION PRESS CAPABILITIES FOR TITANIUM

Company and Location	Extrusion Press Capacity, tons	Liner Diameter, inches	Max Billet Length, inches	Max Circumscribing Circle, inches	Min Cross Sectional Area, in.^{2}	Extruded Length, Capability, feet
Curtiss-Wright Corporation Buffalo, New York	12,000	8 to 28	66	21-1/2	5	75 annealed 40 STA
Harvey Aluminum Company Torrance, California	3,850	6 to 13	36	11	1.0	60 annealed 30 STA
	12,000[a]	Up to 27	44[b]	21	n.a.[c]	60 annealed 30 STA
H. M. Harper Company Morton Grove, Illinois	1,900	5.1 to 6-3/4	27	5-3/8	0.5	60 annealed 30 STA
	1,200	3.3 to 5.1	20	4-3/8	0.125	60 annealed 30 STA
TMCA (Allegheny-Ludlum Steel Corporation) Watervliet, New York	2,200	4 to 8	26	5-1/4	0.5	n.a.
Babcock & Wilcox Company[d] Beaver Falls, Pennsylvania	2,500	4 to 8-1/2	28	6-1/2	n.a.	n.a.
Canton Drop Forging & Mfg. Co., Canton, Ohio[d]	5,500	7-1/2 to 19	44	12	n.a.	n.a.

(a) Available on special inquiry only.
(b) Based on ingot-casting capabilities.
(c) Not available.
(d) Has equipment capabilities but is not now active in supplying titanium extrusions.

2-6 Tubing[1]

2-6.0 GENERAL REMARKS

Hollow tube billets are available from the extrusion suppliers listed in Section 2-5. These blanks are hot extruded to produce tube blanks for subsequent sizing to finish tube either by drawing or tube reducing techniques. Seamless-tube suppliers include:

- Cameron Iron Works, Houston, Texas
- J. Bishop & Company, Malvern, Pennsylvania
- Harvey Aluminum Company, Torrance, California
- LeFiell Manufacturing Company, Santa Fe Springs, California
- Reactive Metals, Inc., Niles, Ohio
- Superior Tube Company, Norristown, Pennsylvania
- Wall Tube & Metal Products Company, Newport, Tennessee
- Whittaker Corporation, San Diego, California
- Whittaker Corporation, Nuclear Metals Division, West Concord, Massachusetts
- Wolverine Tube Division, Calumet and Hecla, Inc., Allen Park, Michigan.

Good-quality seamless tubing of commercially pure (unalloyed) grades is readily available in outside diameters from 0.0625 to 2.5 inches (larger tubes in unalloyed titanium are usually made by roll and weld techniques, although Harvey supplies seamless tube up to 5 inches OD; Cameron supplies heavy-wall tubing from 8 to 36 inches OD). Diameters of 0.75 and 1.00 inch with wall thicknesses ranging from 0.030 to 0.050 inch, are most popular. Wall thicknesses as low as 0.004 inch are available, however. Most of the unalloyed tubing to date has been utilized by the chemical processing industry for anticorrosion applications. However, aircraft applications are indicated in the near future, particularly for cold-worked material in hydraulic tubing requirements.

In all[illegible]ium, seamless tubing is becoming available as a commercial product in Ti-6Al-4V and Ti-3Al-2.5V alloys. Wolverine was first in producing small-diameter Ti-6Al-4V alloy seamless tubing on a development basis. At present, tube sizes of 0.750-inch diameter by 0.035-inch wall, up to 1.5-inch diameter by 0.100-inch wall, are being produced by Wolverine on a commercial basis. Only developmental material is available on material less than 0.750-inch diameter by 0.020-0.100-inch wall and greater than 1.500-inch diameter by 0.035-0.100-inch wall. Some large Ti-6Al-4V alloy tubing (3 to 3.25-inch diameter by 0.125-inch wall) was supplied for the Apollo program by Harvey and Superior. Curtiss-Wright has supplied 5 to 14-inch OD Ti-6Al-4V and Ti-6Al-6V-2Sn alloy tubing for various military programs.

J. Bishop & Company, Reactive Metals, and Superior Tube are known suppliers of Ti-3Al-2.5V alloy tubing on a commercial basis. J. Bishop & Company produces tube diameters up to 1-1 4 inch, with wall thicknesses up to 0.083 inch. Reactive Metals can produce the grade in tubes as small as 0.50-inch diameter. Superior supplies this material in the same sizes available for unalloyed titanium tubing -- from 0.0625-inch OD by 0.004 to 0.015-inch wall thickness to 1.125-inch OD by 0.020 to 0.035-inch wall thickness.

TMCA is a large producer of rolled and welded tubing. Seamless tubing is produced, too, although the indications are that TMCA will go the roll-and-weld route in alloy tubing. For this application, TMCA is researching the Ti-4Al-0.250 alloy which can be texture hardened to have a large biaxially stressed-strength advantage. The welds in this material appear to have the same pole figure configurations as the base material.

Other suppliers of welded tube are:

- J. Bishop & Company, Malvern, Pennsylvania
- Carpenter Steel Company, El Cajon, California
- Valley Metal Corporation, El Cajon, California
- Western Pneumatic Tube Company, Kirkland, California.

These companies supply both unalloyed and alloy tubing in sizes ranging from 1 to 10 inches OD by 0.012 to 0.168 inch wall thickness. Alloys include Ti-6Al-4V, Ti-5Al-2.5Sn, Ti-13V-11Cr-3Al, Ti-8Al-1Mo-1V, and Ti-5Al-5Sn-5Zr.

2-7 Castings[1]

2-7.0 GENERAL REMARKS

Two types of titanium castings are available. These differ according to the type of molding process used but may be classified broadly into either rammed molded or precision molded and cast products.

Techniques for rammed mold casting were the first to be developed for titanium, and these have been produced and used for a number of years. The principle application for these has been in the chemical processing industry (e.g., impellers, pumps, and valves) although rammed mold castings have also found use in hydrofoil and gunboat propeller blades and in aircraft gas turbine starter engines as impellers, inducers, housings, and mounting flanges.

The precision casting of titanium is a relatively new development. Such castings are, however, already finding their way into aircraft-production applications, mainly in aircraft gas-turbine-engine components, but also in airframe components as well.

The principal titanium-casting suppliers are:

Rammed Mold Castings	Precision Castings
Oregon Metallurgical Corp., Albany, Oregon	Misco Div., Howmet Corp., Whitehall, Michigan
Mitron Research & Development Corp.,[a] Waltham, Mass.	Precision Castparts Corp., Portland, Oregon
	REM, Inc.,[a] Albany, Oregon

(a) Production castings available by the end of 1967.

Irrespective of the type of mold used, essentially the same melting process is currently used to produce castings. This is the "skull melting" process, which utilizes a vacuum atmosphere and a consumable electrode as the charge composition. The latter is melted into a water or Na-K-cooled copper crucible to obtain a superheated melt, which is then immediately poured. Approximately one-quarter of the melt is retained as a "skull", lining the interior walls of the cooled, copper crucible.

A tentative ASTM specification (B367-61T) has been developed for castings of unalloyed titanium and the Ti-5Al-2.5Sn and Ti-6Al-4V grades. This specification, however, is not restrictive as to the type of manufacturing methods used to prepare the molds for castings.

2-7.1 RAMMED MOLD CASTINGS

Rammed mold castings have the main advantages of lower cost and (currently) availability in a larger size range than precision castings. The rammed mold, however, carries the necessity for a parting line and is, accordingly, more limited in as-cast dimensional tolerances. The standard dimensional tolerances presently offered are ±0.020 inch to 3 inches plus 0.003 inch for each additional inch across the parting line. The minimum thickness is considered to be 0.200 inch.

The present maximum casting weight (available from the Oregon Metallurgical Corporation) is approximately 300 pounds. The maximum overall casting dimensions are 5 feet in length, 3 feet in width, and 2 feet in height. Maximum poured weight, including gates, risers, etc., is about 600 pounds.

Graphite is the principal ingredient in current rammed molds, and some surface reaction of the titanium normally occurs at the mold-metal interface, especially where a mass of titanium surrounds protruding thinner sections of graphite, as in cored parts, fillets, and curves. This tendency toward a contaminated surface in rammed graphite mold castings necessitates the allowance of at least 5 to 10 mils of extra material for removal by machining in critical applications. For certain applications, the degree of surface contamination is not critical and the castings are used after normal clean-up by grit blasting. Such a standard surface finish is equivalent to a smooth, sand casting finish.

Table 2-7.1-1 lists the nominal compositions and minimum specified tensile properties for unalloyed titanium and six titanium alloys, which are available from the Oregon Metallurgical Corporation in rammed mold castings.

2-7.2 PRECISION CASTINGS

The main advantages of precision-cast titanium parts include close dimensional control surface smoothness, and virtual freedom from surface contamination. Dimensional tolerances can be held to within ±0.005 in./in. with surface finishes ranging from 90 to 125 RMS. Minimum section thicknesses down to about 0.060 inch are possible, depending on part configuration. Precision castings containing section thicknesses up to about 8 inches have been produced.

Currently, precision castings are available from Misco in sizes up to 24 inches in diameter

and 24 inches in height, having a poured weight to about 200 pounds. REM, Inc., has been limited to castings totaling about 5 pounds in weight but, by the end of 1967, intends to complete installation of a furnace capable of producing castings totaling up to 400 pounds in weight.

The mold materials and molding processes used in making precision castings are largely proprietary and apparently vary among the different producers.

Table 2-7. 1-1 lists the nominal compositions and minimum specified tensile properties for unalloyed titanium and two titanium alloys which are available from Misco in precision castings. Misco has also prepared experimental precision castings of the Ti-6Al-2Sn-4Zr-2Mo and Ti-6Al-6V-2Sn alloys. In addition to the material specifications cited in Table 2-7. 1-1, Misco has also developed three tentative specifications covering visual, radiographic, and fluorescent penetrant inspection processes for precision titanium castings. These are identified as VIS-RMD-100, RAD-RMD-200, and ZYL-RMD-300, respectively.

TABLE 2-7. 1-1. ROOM-TEMPERATURE TENSILE PROPERTIES OF TITANIUM CASTINGS[a]

Nominal Composition, percent	Ultimate Strength, ksi	Yield Strength (0. 2 Percent Offset), ksi	Elongation, percent in 4D	Reduction in Area, percent	Pertinent Specifications[b]
		Rammed Mold Castings			
Commercially Pure Ti	65-105	55-95	12	--	OMC-105
Ti-0. 15Pd	65-105	55-95	12	--	OMC-103
Ti-2Cu	75	60	12	20	OMC-168
Ti-5Al-2. 5Sn	115	105	10	--	OMC-166A
Ti-6Al-4V	137	120	6	10	OMC-164B
Ti-4Al-4Sn-8Zr-2V	150	130	6	10	OMC-167TA
Ti-4Al-4Sn-8Zr-1V-1Cr	150	130	6	10	OMC-167T
		Precision Castings			
Commercially Pure Ti	80	70	15	30	MET-RMD-2
Ti-5Al-2. 5Sn	115	110	10	20	MET-RMD-3
Ti-6Al-4V	130	120	6	12	MET-RMD-1
	130[c]	120[c]	8[c]	16[c]	

(a) Unless a range is shown, values represent minimum properties determined either on separately cast test bars or on samples machined from castings.

(b) OMC sequence represents Oregon Metallurgical Corporation specifications, while MET-RMD sequence represents tentative Misco material specifications.

(c) Annealed after casting.

2-8 Fasteners[1]

2-8.0 GENERAL REMARKS

Fasteners are more properly classified as a finished product rather than as a mill product. Titanium fasteners are made from wire and rod in diameters ranging from 0.150 inch to greater than 1.0 inch. The largest use of such fasteners falls within the range of 0.25 to 0.50 inch diameters. Because of seizing and galling problems and because nuts do not constitute much of the fastener weight (15 percent usually), nuts are often fabricated from some other material (A-286 steel is common). In general, the cost of titanium nuts has been too high, in comparison to bolts, for the weight saved to make their use attractive.

It has been estimated that the current market for titanium fasteners is roughly around 200,000 pounds per year. A large percentage of this output is in Ti-6Al-4V alloy although fasteners are being produced in at least nine other alloys. The major field of use is in engines and air frames for manned aircraft with usage in missiles and space vehicles being quite limited. Titanium fasteners are generally limited to shear-type fasteners since in shear titanium maintains a strength-weight advantage over steel while in tension the same advantage is not always found.

A number of fastener companies were recently surveyed pertaining to their 1967 status of titanium fastener development. The following 13 companies responded and indicated their capabilities in providing fasteners of the alloys and types listed in Table 2-8.0-1.

(1) Air Industries of California, Gardenia, California
(2) Briles Manufacturing, El Segundo, California
(3) Deutsch Fastener Corporation, Los Angeles, California
(4) Elastic Stop Nut Corporation of America, Union, New Jersey
(5) H. M. Harper Company, Morton Grove, Illinois
(6) Hi-Shear Corporation, Torrance, California
(7) Huck Manufacturing Company, Detroit, Michigan
(8) Kaynar Manufacturing Company, Fullerton, California
(9) Missilecraft Company, Beverly Hills, California
(10) National Screw and Manufacturing Company
- California Division, Los Angeles, California
- Chandler Products Division, Cleveland, Ohio
- National Division, Cleveland, Ohio

(11) Rosan, Inc., Newport Beach, California
(12) Townsend Company, Cherry Rivet Division, Santa Ana, California
(13) Valley Bolt Corporation, Sylmar, California.

TABLE 2-8.0.1. TITANIUM FASTENER AVAILABILITY

Data selected from results obtained during a 1967 survey.

Nominal Composition, %	Status and Source(a) of Fastener Types Indicated											
	Bolts		Nuts		Rivets		Screws		Pins	Collars	Studs	Inserts
	C	D	C	D	C	D	C	D	C	C	C	C
Commercially pure Ti	--	--	--	--	--	--	--	--	--	7	--	--
Ti-7Al-12Zr	--	9	--	--	--	--	--	--	--	--	--	--
Ti-8Al-1Mo-1V	7	--	--	--	--	--	--	--	--	--	--	--
Ti-3Al-2.5V	--	--	--	--	--	12	--	--	--	7	--	--
Ti-4Al-4Mn	2,5,9	--	5	--	--	--	5,9	--	--	--	9	--
Ti-4Al-4Mo-4V	6	--	6	--	6	--	--	--	6	--	--	--
Ti-6Al-4V	1,2,5,6, 7,9,10, 11,13	--	4,5,6	8,11	6,10, 13	1,3,11, 12	5,9,10, 11	3	6	--	9,11	11
Ti-6Al-6V-2Sn	6	2	6	--	6	--	--	--	6	--	--	--
Ti-1Al-8V-5Fe	7	2,9	--	--	--	--	--	--	--	--	--	--
Ti-1Al-8Mo-5Fe	--	11	--	--	--	--	--	11	--	--	--	--
Ti-13V-11Cr-3Al	7	--	--	--	--	12	--	--	--	--	--	--

(a) C = commercial status; D = developmental status. Companies are coded by the number designations given above.

2-20 References

(1) Personal communication.
A large amount of the information summarized in this section was obtained through personal communications with the various companies involved with particular subjects of interest. Note is made of this fact where no other references are cited. Where other references are cited, it is also noted that supplementary information was often obtained by personal contact with the company (companies) involved.

(2) Wood, R. A., "A Tabulation of Designations, Properties, and Treatments of Titanium and Titanium Alloys", Battelle Memorial Institute, DMIC Memorandum 171 (July, 1963).

(3) Courtesy of Wyman-Gordon Company.

(4) Henning, H. J., Sabroff, A. M., and Boulger, F. W., "A Study of Forging Variables", Battelle Memorial Institute, ASD TR 61-6-876 (May, 1962).

(5) Henning, H. J., and Frost, P. D., "Titanium-Alloy Forgings", Battelle Memorial Institute, DMIC Report 141 (December, 1960).

(6) Christiana, J. J., "Improved Methods for the Production of Titanium Alloy Extrusions", Republic Aviation, Final Report on AF 33(600)-34098, RTD TR 63-7-556 (December, 1963).

(7) Levine, M. H., "B-120VCA Titanium Alloy Extrusion Program", Republic Aviation PR No. 2 on AF 33(657)-8746, ASD TR 8-103, Volume II (February, 1963).

(8) Preliminary information reported by Republic Aviation under Contract AF 33(615)-1674.

(9) Preliminary information reported by Lockheed-Georgia Company under Contract AF 33(615)-3839.

SECTION 3
Machining and Forming

3-0 General Machining Considerations

3-0.0 INTRODUCTION

Fifteen years ago, titanium had the reputation of being very difficult to machine compared to common constructional materials. However, Government and private research, continuing experience, and the combined use of the information generated have progressively improved this situation. As various companies using titanium alloys gain experience, there is a steady improvement in rates of metal removal. This increase is caused partly by increased uniformity in the alloy, partly by strict attention to the machining conditions required for titanium, and by gradual refinements in tool materials, tool geometries, and cutting fluids.

Today, tools and techniques are available for machining titanium efficiently. In fact, some machining operations give more consistent results on titanium than they do on some grades of steel. A bonus factor is the ease of attaining good surface finishes. Roughness values as low as 20 to 30 microinches can be obtained on some titanium parts without too much trouble.

3-0.1 MACHINING TITANIUM

3-0.1.1 Machinability Factors

The relative ease of metal removal for equal tool lives can be expressed in terms of the machinability ratings of different metals. In this light, the machinability of unalloyed titanium is similar to that of the annealed austenitic stainless steels, while titanium alloys are more comparable to 1/4-hard and 1/2-hard stainless steels [1,2]. This comparison is also justifiable from another viewpoint, i.e., that both materials produce a tough, stringy chip. Actually, however, austenitic stainless steel usually requires heavier feeds to penetrate below a heavily strain-hardened skin, whereas titanium, a material that does not strain harden as severely, does not necessarily require heavy feeds. Table 3-0.1.1-1 shows the approximate machinability ratings of titanium alloys stainless steel, and other alloys of interest to the aerospace industry. [3]

Generally speaking, machining problems for titanium can originate from four sources: high cutting temperatures, chemical reactivity and abrasiveness with tools, and a relatively low modulus of elasticity. A built-up edge, however, does not form on tools used to machine titanium. Although this phenomenon accounts for the characteristically good finish on machined surfaces, it also leaves the cutting edge naked to the abrading action of the chip peeling off the work. In addition, titanium produces a thin chip, which flows at high velocity over the tool face on a small tool-chip contact area. This, plus the high strength of titanium produces high contact pressures at the tool-chip interface. This combination of events and the poor heat conductivity of titanium results in unusually high tool-tip temperatures. [2]

The cutting temperature achieved at the tool point depends partly on the rate at which heat is generated from the tool forces involved at the tool point, from the tool forces involved, and partly on the rate at which it is removed by the chip, the cutting fluid, and by conduction through the tool.

The heat-transfer characteristics of the chip and work material depend on thermal diffusivity, which is a function of density, specific heat, and thermal conductivity. Since titanium exhibits poor thermal diffusivity, as indicated in Table 3-0.1.1-2, tool-chip interface temperatures are higher than they would be when machining other metals at equal tool stresses. The higher temperatures in the cutting zone lead to rapid tool failure unless [illegible]ficient cooling is provided by suitable cutting fluids. [3]

The strong chemical reactivity of titanium with tool materials at high cutting temperatures and pressures induces galling, welding, and smearing, since an alloy is continuously formed between the titanium chip and the tool material. [5] This alloy passes off with the chip, producing tool wear. Titanium reactivity also shows up when the tool dwells in the cut, even momentarily as in drilling. In this case, the cutting temperature drops, causing the chip to freeze to the tool. When cutting is resumed, the released chip leaves a layer of titanium on the cutting edge. This layer then picks up additional titanium to form an "artificial" built-up edge, which spalls off, taking part of the tool edge with it. This undesirable situation can be prevented by eliminating dwelling in the cut, or by dressing the tool to remove the titanium layer before cutting is resumed.

Abrasion by surface contamination or scale on titanium can notch cutting tools at the depth-of-cut line. Consequently, this contamination should be removed before machining.

The stiffness of a part, determined by the shape and the modulus of elasticity of the workpiece material, is an important consideration when designing fixtures and selecting machining conditions since the thrust force, which deflects the part being machined, is considerably greater for this metal than for steel. Since the modulus of elasticity for for titanium is only about half that of steel, a titanium part may deflect several times as much as a similar steel part during machining, creating tolerance and tool-rubbing problems. In addition, titanium may shrink on steel drills, reamers, and taps because of differences in the thermal expansion of the materials involved.

TABLE 3-0. 1. 1-1. MACHINABILITY RATINGS OF TITANIUM AND ITS ALLOYS RELATIVE TO OTHER SELECTED MATERIALS(3,4)

Alloy	Type	Condition(a)	Hardness, Bhn.	Rating(b)
2017	Aluminum all[illegible]			300
B1112	Resulfurized st[illegible]	HR		100
1020	Carbon steel	CD		70
4340	Alloy steel	A		45
Titanium	Commercially pure	A		40
302	Stainless steel	A		35
Ti-5Al-2.5Sn	Titanium alloy	A	310	30
Ti-8Mn	Titanium alloy	A		25
Ti-6Al-4V	Titanium alloy	A		22
Ti-8Al-1Mo-1V	Titanium alloy	A		22
Ti-6Al-6V-2Sn	Titanium alloy	A		20
Ti-6Al-4V	Titanium alloy	HT	365	18
Ti-6Al-6V-2Sn	Titanium alloy	HT	365	16
Ti-13V-11Cr-3Al	Titanium alloy	A		16
Ti-13V-11Cr-3Al	Titanium alloy	HT	365	~12
HS25	Cobalt base	A		10
Rene 41	Nickel base	HT		6

(a) Usual condition for machining
T4: Solution-heat-treated and artifically aged condition
HR: Hot-rolled condition
A: Annealed Condition
HT: Solution-treated-and-aged condition
CD: Cold-drawn condition.
(b) Based on AISI B1112 steel as 100.

TABLE 3-0. 1. 1-2. PHYSICAL PROPERTIES AND RELATIVE HEAT-TRANSFER PROPERTIES OF COMMERCIALLY PURE TITANIUM, 75ST ALUMINUM ALLOYS, AND AISI 1020 STEEL(3)

Property	Commercially Pure Titanium	75ST Age-Hardened Aluminum	AISI 1020 Steel
Density (ρ), lb/in.^{3}	0.163	0.101	0.290
Thermal Conductivity (k), Btu/(ft^2) (hr) (F) (in.)	105	845	390
Specific Heat (C_p), Btu/(lb) (F)	0.13	0.21	0.117
Volume Specific Heat (ρ C), Btu/(in.^{3}) (F)	0.021	0.021	0.031
Thermal Diffusivity	4950	39,800	11,500

3-0.1.2 General Machining Requirements

Successful machining of titanium and its alloys requires the use of high-quality machine tools and cutting tools; an absolute minimum of vibration; rigid setups; and faithful observance of recommended machining practices.

Machine tool selection is a primary factor; just any machine will not do. In fact, machine tools used for machining titanium must be in excellent condition and possess certain basic attributes that insure vibration-free operations. These include dynamic balance of rotating elements; true running spindles; snug bearings, slides, and screws; sturdy frames; wide speed/feed ranges; and ample power to maintain speed throughout cutting. Undersized or under-powered machines should be avoided. Certain locations of machines near or adjacent to heavy traffic also can induce unwanted vibration and chatter during machining.[6,7] Specific information and data on machine-tool requirements are presented in each specific machining operation covered herein.

Rigidity of operation is also a very important consideration. Generally, it is obtained through the use of adequate clamping and by minimizing deflection of work and tool during machining. In milling, this means strong, short tools, machining close to the table, rigid fixturing, frequent clamping of long parts, and the use of backup support for thin walls and delicate workpieces. Rigidity in turning is achieved by machining close to the spindle, gripping the work firmly in the collet, and providing steady or follow rests for slender parts. Drilling requires short drills, positive clamping of sheet, and backup plates on through holes.[6]

Cutting speed is important in all machining operations and is a very critical variable for titanium. As shown in Figure 3-0.1.2-1, cutting

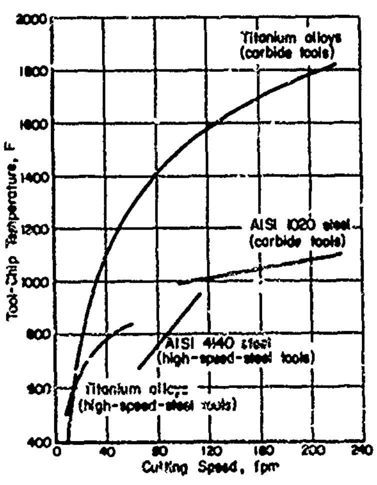


FIGURE 3-0.1.2-1. EFFECT OF CUTTING SPEED ON CUTTING TEMPERATURE FOR CARBIDE AND HIGH-SPEED STEEL[3,8]

speed has a pronounced effect on tool-chip temperature. Accordingly, it can be deduced that excessive speeds could cause overheating and short tool life. Consequently, speeds are limited to relatively low values, unless adequate cooling can be supplied at the cutting site. However, all machining variables should be carefully selected to effect optimum machining rates.

All machining operations require a positive uniform feed achieved mechanically. The cutting tool should never dwell or ride in the cut without removing metal. As an added precaution, all cutters should be retracted when they are returned across the work. The cutter should be up to speed and should maintain this speed as the cutter takes the load.

In summary, correct machining setups for titanium require strong, sharp cutting tools; positive feeds; relatively low cutting speeds; and certain types of cutting fluids. Improper cutter rigidity and/or geometry can contribute to vibration. Spindle speeds and feeds should be verified on each machine to ensure correct cutting conditions, since small changes in cutting conditions can produce large changes in tool life. All machining variables should be carefully selected to effect optimum machining rates. The recommended speeds and feeds suggested in this manual are intended to serve as guides to assist the machinist in the selection of these proper cutting conditions.

3-0.1.3 Cutting Tools

High-quality cutting tools, properly ground, are needed for all machining operations. The face of the tool should be smooth, and the cutting edges sharp and free of feather burrs. Milling cutters, drills, and taps should be mounted to run true. Lathe tools should usually cut on dead center. In a multiple-tooth cutter like a mill or a drill, all teeth should cut the same amount of material.

High-speed steel, cast alloy, and carbide tools are used, the choice depending on seven basic factors, including:

(1) The conditions of the machine tool
(2) The rigidity of the system
(3) The type of cut to be made
(4) The surface condition of the titanium
(5) The amount of metal to be removed
(6) The metal removal rate
(7) The skill of the operator.

Carbide tools require heavy-duty, amply powered, vibration-free machine tools and rigid tool-work setups to prevent chipping. If these two basic conditions cannot be met, then high-speed steel tools give better results.

Carbide cutting tools are usually selected for high-production items, extensive metal-removal operations, and scale removal. The so-called nonferrous or cast-iron grades of carbides are used for titanium. These have been identified as CISC Grades C-1 to C-4 inclusive by the Carbide Industry Standardization Committee. A partial list of companies producing these grades of carbide cutting tools is given in Table 3-0. 1. 3-1.

Although competitive brands of cutting tools classified under the same grade are similar, they are not necessarily identical. Variations in tool life should be expected from carbides produced by different manufacturers and between lots made by the same producer. For this reason, some aircraft companies specify their own lists of interchangeable carbide tools made by approved manufacturers.[3]

High-speed steel tools can be utilized at low production rates, but tool life is low by ordinary standards. Both the tungsten and molybdenum types of conventional high-speed steel have been used. Cobalt is often added to these steels to increase their red hardness above 1000 F. Conventional high-speed steels normally become too soft to be cut effectively much in excess of this cutting temperature. New super-high-speed steels (M41 to M44) are also available and are used with good results. Table 3-0. 1. 3-2 shows the wide choice of compositions of high-speed steels available to the tool engineer.

Certain precautions must be observed when cobalt high-speed steels and super high-speed steels are used. They are sensitive to checking and cracking from abrupt temperature changes such as might occur during grinding. Consequently, steps should be taken against any kind of sharp, localized overheating or sudden heating or cooling of these steels. They are more brittle than conventional high-speed steels and hence are not usually suitable for razor-edged-quality tools. In addition, precautions must be taken to protect these high-speed steels from excessive shock and vibration in service.[3]

Cast cobalt-chromium-tungsten alloys are used for metal cutting at speeds intermediate between carbide and high-speed steel. The three main constituents of the alloys -- cobalt, chromium, and tungsten -- are combined in various proportions to produce different grades, as shown in Table 3-0. 1. 3-3.[3]

3-0. 1. 4 Cutting-Fluid Considerations

Cutting fluids are used on titanium to increase tool life, to improve surface finish, to minimize welding, and to reduce residual stresses in the part. Soluble oil-water emulsions, water-soluble waxes, and chemical coolants are usually used at the higher cutting speeds (75 to 100 fpm and higher) where cooling is important. Low-viscosity sulfurized oils, chlorinated oils, and sulfochlorinated oils are used at lower cutting speeds (below 75 fpm) to reduce tool-chip friction and to minimize welding to the tool.[4] Cutting oils may have either mineral oil or mineral oil-lard oil bases. All cutting fluids have been identified as follows for use in subsequent machining tables:

Fluid Code Number[a]	Cutting Fluid Type
1	Soluble oil-water emulsion (1:10)
2	Water-soluble waxes
3	Chemical coolants (synthetics, barium hydroxide, etc.)
4	Highly chlorinated oil
5	Sulfurized oil
6	Chlorinated oil
7	Sulfochlorinated oil
8	Rust-inhibitor types (such as nitrite amine)
9	Heavy-duty soluble oil (such as chlorinated, barium sulfonated extreme-pressure additive types).

(a) Code numbers used in this handbook.

For many machining operations, it is possible to specify practical cutting fluids by using class designations such as "soluble oil", "sulfurized oil", and "sulfo-chlorinated oil". For some of the difficult-to-machine alloys, however, class designations are sometimes inadequate. Many fluids that improve machinability are complex, often proprietary, and sometimes contain unidentifiable active compounds. The best way for specifying such fluids is by trade name, provided the formulations are not altered later under the same trade name. The Machining Data Handbook[9] lists 19 companies producing cutting fluids for titanium.

Some companies use soluble oil-water emulsions for roughing cuts and oil-base cutting fluids for finishing cuts. Soluble oil-water emulsions are also used for turning, face milling, and slab milling; oil-base fluids for reaming and tapping.[10]

Both flood and mist applications are used, depending on the cutting speed and cutting fluid used. Flood application through multiple nozzles to cover the cutting tool and immediate cutting area can be used for oil-base or water-base fluids. This form of application is not recommended for those high cutting speeds that would throw off the fluids.[9]

The mist system provides cooling and/or lubrication to inaccessible areas, visibility of the cutting zone, and better tool life (or lower costs) in some instances. Water-base fluids are

TABLE 3-0.1.3-1. TOOL-MATERIAL GUIDE FOR CARBIDES

CISC[b] Grade	Partial List of Carbides[a] Made by Various Manufacturers												
	Adams	Carmet	Carboloy	Firth Loach	Firthite	Kenna-Metal	Newcomer	Sandvik Coromant	Tallide	Tungsten Alloy	Valenite	VR/Wesson	Willey
C-1	B	CA3	44A	FA5	H	K1	N10	H20	C89	9	VC1	2A68, VR54	E8, E13
C-2	A	CA4	883, 860	FA6	HA	K6	N20	H1P	C91	9H	VC2	2A5, VR54	E6
C-3	AA	CA7	905	FA7	HE	K8	N30	H1P	C93	9C	VC3	2A7	E5
C-4	AAA	CA8	999	FA8	HF	K11	N40	HO5	C95	98	VC4	2A7	E3
C-5	DD	CA51	78C	FT3	TQ4	KM	N5C	S6, S4	S88	11T	VC5	EE, VR77	945
C-5A	434	CA610	370	FT41, FT5	TXH	K21	--	S1P	S88X	96	VC125	VR77, VR75	8A
C-6	D	CA609	788	FT4	FXH, TA	K2S	N60	S2	S90	10T	VC6	VR75	710
C-7	C	CA608	78	FT6	TXL	K5H	N70	SIP	S92	8T	VC7	E, VR73	606
C-7A	548	CA606	350	FT61	T16, TXL	K4H	--	--	S92X	5S	--	VR73	6A
C-8	CC	CA605	330	FT7	T31, WF	K7H	N80	FO2	S94	5S	VC8	EH	509, 4A

(a) For the same CISC grade, there seem to be no truly equivalent carbides of different brands. Where two carbide grades from the same manufacturer are shown for the same CISC grade, the first is sometimes recommended.

(b) Carbide Industry Standardization Committee.

Notes:

(1) The following chip-removal applications have been used for the CISC grade indicated. It will be noted that some grades specify the type of metal removal for which they are best suited.

C-1 Roughing Cuts - cast iron and nonferrous materials
C-2 General Purpose - cast iron and nonferrous materials
C-3 Light Finishing - cast iron and nonferrous materials
C-4 Precision Boring - cast iron and nonferrous materials
C-5 Roughing Cuts - steel
C-5A Roughing Cuts and Heavy Feeds - steel
C-6 General Purpose - steel
C-7 Finishing Cuts - heavy feeds - steel
C-7A Finishing Cuts - fine feeds - steel
C-8 Precision Boring - steel

(2) This table can function only as a guide. The so-called "best grade" may differ for each specific job even if the material being machined is the same. The final selection can be made only by trial and error. Instructions regarding the specific use and application of any competitive grade should be obtained directly from the manufacturer.

TABLE 3-0.1.3-2. COMPOSITIONS OF HIGH SPEED STEELS

Group[a]	AISI Code[b]	Composition, weight percent				
		Tungsten	Chromium	Vanadium	Cobalt	Molybdenum
Tungsten	T-1	18	4	1	--	--
	T-4	18	4	1	5	--
	T-5	18.5	4	1.75	8	--
	T-6	20	4	2	12	--
	T-8	14	4	2	5	--
	T-15	14	4	5	5	--
Molybdenum	M-1	1.5	4	1	--	8
	M-2	6	4	2	--	5
	M-10	--	4	2	--	8
	M-3	6	4	2.75	--	5
	M-3, Type 1	6.25	4	2.50	--	5.70
	M-3, Type 2	5.6	4	3.3	--	5.50
	M-4	5.50	4	4	--	4.50
	M-6	4	4	1.5	12	5
	M-7	1.75	3.75	2	--	8.75
	M-30	2	4	1.25	5	8
	M-33	1.75	3.75	1	8.25	9.25
	M-15	6.5	4	5	5	3.5
	M-34	2	4	2	8	8
	M-35	6	4	2	5	5
	M-36	6	4	2	8	5
	M-41	6.25	4.25	2	5	3.75
	M-42	1.5	3.75	1.15	8	9.5
	M-43	1.75	3.75	2	8.25	8.75
	M-44	5.25	4.25	2.25	12	6.25

(a) There is little difference in properties between the molybdenum and tungsten types of high-speed steel. Although each group has its supporters, extensive laboratory and production comparisions of comparable grades of the two types have not consistently established any outstanding superiority for either group.

(b) When greater than average red hardness is needed, cobalt-containing grades are recommended. So-called parallel grades in the molybdenum and tungsten groups are not necessarily comparable. Fox example, special-purpose steels such as T-6, T-8, T-15, and M-6, M-35, and M-36 seem to have no close counterparts in the opposite group. The unique compositions and properties of these steels often suit them to certain applications without competition.

preferred over the oil-base fluids because of a possible health hazard of oil mists.[9]

Fluids, whether flood or mist applied, must be directed to give maximum cooling and/or lubrication to the tool/work interface. Care must be taken not to direct the fluid directly onto the chip, thereby blocking the flow of fluid to the zone of maximum heat.[11]

Although chlorinated oils are being used in some cases on titanium and its alloys, they should be avoided if nonchlorinated fluids satisfy the machining requirements. Chloride residues from these fluids may lead to stress-corrosion cracking of parts during service. This cracking situation is discussed more fully in Section 1-0.5. If chlorinated fluids are used on titanium, the residues must be removed promptly with a non-chlorinated degreaser such as methyl ethyl ketone (MEK). Fundamentally, it is always good practice to remove all cutting fluid or lubricant residues regardless of type completely from work-pieces, especially before any heating operation. Furthermore, due consideration should be given to the difficulties of washing complex assemblies.

Most of the prime defense contractors have well-defined machining and cleaning procedures relating to the use of chlorine-type cutting fluids

TABLE 3-0.1.3-3. TOOL-MATERIAL GUIDE FOR CAST ALLOYS[3]

	Composition, percent									Hardness,
	Co	Cr	W	C	Ni	Fe	Ta	B	Other	RC
Stellite 19[a]	50.6	31	10.5	1.9	--	3.0 max	--	--	3.0	55
Stellite 3[b]	46.5	30.5	12.5	2.45	3.0 max	3.0 max	--	--	2.0	60
Tantung G[c]	46	28	16	2.0	--	2.0	5	0.2	2.0	--
Stellite Star-J[d]	40.5	32	17	2.5	2.5 max	3.0 max	--	--	2.5	61
Stellite 98M2[e]	37.5	30	18.5	2	3.5	2.5 max	--	--	6	63

(a) Possesses the highest resistance to shock loading or intermittent-cutting effect, but the lowest red hardness of the stellites listed.

(b) Possesses higher hardness, but lower impact strength than Stellite 19 If Stellite 3 can handle the shock conditions of cutting, it is preferable to Stellite 19.

(c) A good compromise of hardness and shock resistance.

(d) Among the stellites, the hardness of Star-J is second only to 98M2. It should machine metal faster than Stellites 3 and 19 under moderate impact conditions. Stellite Star-J is suitable for milling cast iron.

(e) Possesses the highest hardness of all stellites, but only fair impact strength.

for titanium alloys. Subcontractors are advised to make certain that they are following the latest practices required by prime contractors. Additional note should be taken of the fact that different cleaning procedures may be specified for machining assemblies and for detailed parts.[12]

3-0.1.5 Scrap Prevention

Since titanium is a relatively expensive metal, every effort should be made to avoid waste. Table 3-0.1.5-1 illustrates the common sources of scrap and their importance in different machining operations, and suggests ways of preventing scrap.

Any scrap-prevention program requires adherence to the basic recommendations for machining titanium stated previously. In addition to those practices, parts should be handled and transported with reasonable care. Nicks and scratches must be avoided, both on parts in process and on finished parts. Hence, suitable containers or paper separators* should be used for parts in process to prevent damage in handling and storage.

The machining and grinding of titanium normally require closer supervision than do operations on other metals, not only to prevent scrap, but also to detect defective parts early in the processing schedule.

3-0.1.6 Hazards and Safety Considerations

Titanium by itself is not particularly hazardous, although a potential explosion hazard may exist if very finely divided titanium is present in air in the proper proportions. The fire hazard can be more real. Fine chips and turnings can be ignited under certain conditions. Titanium turnings also may ignite when the metal is cut at high speeds without the adequate use of coolants. In the same manner, dry grinding can cause trouble due to the intense spark stream. Finally, chip accumulations from poor housekeeping habits and improper storage produce likely sites for titanium fires.[13-18]

From the health viewpoint, no adverse physiological reaction from titanium has been reported. However, barium compounds, such as barium hydroxide, used as cutting fluids may be hazardous to personnel unless suitable precautions are taken to protect machine operators. Barium compounds may possess both acute and chronic toxicity if inhaled at high concentrations. Consequently, positive measures must be taken to exhaust all fumes and mist

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* "Cel-Fibe" cellulose wadding or equivalent.[16]

TABLE 3-0.1.5-1. SOURCES OF SCRAP FOR VARIOUS MACHINING OPERATIONS AND THE CORRECTIVE ACTIONS NEEDED[3]

	Sources of Scrap							
	Burned Surfaces	Rough Finish	Chatter Marks	Dimensional Discrepancies	Residual Stresses	Distortion	Broken Tools	Handling Scratches
	Incidence of Scrap for Machining Operation Shown							
Operation								
Turning		x	x	x	x	x		x
Milling		x	x	x				x
Drilling				x			x	x
Tapping		x		x			x	x
Grinding	x	x		x	x	x		x
Belt grinding	x				x			x
Cut-off	x							
Sawing				x				x
	Corrective Action Needed to Avoid Defects Indicated Above							
Corrective Action								
Strong, sharp tools		x		x	x	x	x	
Dressed wheels	x					x		
Positive chip removal		x	x					
More rigid setups		x	x	x				
Modern machine tools			x	x				
Speed/feed/cutting fluid		x		x	x	x	x	
Careful handling								x
Stress relief					x	x		

from the machining area. The recommended maximum atmospheric concentration per 8-hour day is 0.5 mg per cubic meter of air.[1,12,18-22]

Safety considerations are concerned with both preventive and emergency measures. Preventive measures generally mean that good housekeeping practices must be maintained at all times.[3,13-15,17] Specifically, they involve:

(1) Regular chip collection and storage in covered containers (once a day)

(2) Removal of containers to an outside location

(3) Keeping of machine ducts and working areas clean of titanium dust, chips, and oil-soaked sludge

(4) Cleaning area and equipment of all oil and grease, and removal of rags and waste subject to spontaneous combustion.

If a fire starts, it should be smothered by using dry powders developed for combustible metal fires. These include graphite powder, powdered limestone, absolutely dry sand, and dry compound extinguisher powder for magnesium fires.[14-18]

Carbon tetrachloride or carbon dioxide extinguishers should not be used.[19-21,23][14-16,18] Water or foam should never be applied directly to a titanium fire. Water accelerates the burning rate and may cause hydrogen explosions. However, water can be applied to the surrounding area up to the edges of the fire to cool the unignited material below the ignition point[13-18]

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3-1 Conventional Machining and Sawing

3-1.1 MILLING OPERATIONS

3-1.1.0 Introduction

Milling is an intermittent cutting operation that can be difficult to control because of the large number of variables involved. Welding and edge chipping are the basic problems when milling titanium.[1-5] The amount of titanium welded on cutter edges is proportional to the chip thickness as each tooth leaves the cut. The weld metal and part of the underlying cutting edge then chips off as each tooth reenters the cut, thus starting a wearland. Welding increases progressively, and the wearland grows until sudden tool failure occurs. This progressive tool chipping and wear phenomenon also produces a gradual surface-finish deterioration and a loss of tolerance. Both factors can become serious unless the worn or damaged tool is replaced.[3]

Other problems to be faced include heat, deflection, and abrasion. High cutting temperatures soften chips, which tend to clog and load milling cutters. Deflection of thin parts and slender milling cutters promotes rubbing and adds heat. Abrasive oxide surfaces on titanium can notch the cutter at the depth-of-cut line.

Another problem in milling titanium, particularly in the case of extrusions, is distortion originating from the release of stresses originally imposed by the basic mill processing operation. Distortion occurs when unequal amounts of metal are removed from opposite surfaces, or by the machining operation itself.

The welding/chipping behavior described can be minimized by providing thin exit chips characteristic of down (climb) milling.[5,6] Slower speeds and light feeds also reduce chipping and permit lower cutting temperatures. Water-base coolants also reduce cutting temperatures and hence minimize galling. Chemical removal of any oxide skin before machining will alleviate the abrasion problem. Stress relief in fixtures before final machining overcomes the distortion problem.

In spite of the difficulties described, milling operations can produce titanium parts in a variety of shapes and sizes to aircraft standards of surface finish and dimensional accuracy. A surface finish of 63 microinches rms or better is readily attainable and values as low as 17 microinches rms are possible in finishing cuts.[5]

3-1.1.1 Milling Machines

Heavy-duty horizontal or vertical knee-and-column milling machines are required for face milling, end milling, and pocket milling of titanium. Heavy-duty, fixed-bed milling machines also can be used for face milling and end milling of large titanium workpieces.

Numerically controlled, vertical profile milling machines, or tracer-controlled milling machines are usually recommended for profile and pocket milling operations.

Backlash elimination and snug table gibs are requirements for milling machines used on titanium.[7]

Generally speaking, 10 to 15 horsepower is usually sufficient for milling titanium. This means, for example, a No. 2 heavy-duty or a No. 3 standard knee-and-column milling machine. However, the large machines often needed to accomodate large parts may have as much as 25 to 50 horsepower available.

3-1.1.2 Milling Cutters, Design, and Quality

The choice of the milling cutter used depends on the type of machining to be done.[8] Face mills, rotary face mills, plain milling cutters, and slab mills are used for milling plane surfaces. End mills are used for light operations such as profiling and slotting. Form cutters and gang-milling cutters are used to produce shaped cuts. All cutters need adequate body sections and tooth sections to withstand the cutting loads. Helical cutters are preferred for their smoother cutting action. The use of the smallest diameter cutter with the largest number of teeth without sacrificing necessary chip space minimizes chatter and deflection.[9-11]

Tool angles of a milling cutter should be chosen to promote unhampered chip flow and immediate ejection of the chip. The controlling angles in this regard include the axial rake, radial rake, and corner angles. These angles should be chosen to provide a positive angle of inclination to lift the chip from the machined surface.

Rake angles are not especially critical. Some investigators have reported that tool life progressively improves as the radial rake is reduced from +6 to 0 degrees and down to -10 degrees.[2] Positive rake angles are generally used on high-speed steel cutters, but occasionally it is necessary to reduce the rake to zero to overcome a tendency for the cutter to "dig-in", or to chip prematurely.

The use of a corner angle plus a small nose radius also provides a longer cutting edge. This distributes cutting forces over a greater area, causing less pressure. It also aids in dissipating the heat of cutting.[2,12] A 30 to 45-degree chamfer also can produce a longer cutting edge and a wider, thinner chip; however, a corner angle is usually more effective than a chamfer.[1]

Relief angles are probably the most critical of all tool angles when milling titanium. Relief angles around 12 degrees give longer tool life than the standard relief angles of 6 or 7 degrees. If chipping occurs, the 12-degree relief angles should be reduced toward the standard values. Generally, relief angles less than 10 degrees may lead to excessive smearing along the flank, while angles greater than 15 degrees weaken the tool and encourage "digging-in", as well as chipping of the cutting edge.[2,3,11]

All cutters should be ground and mounted to run absolutely true, to make certain that all teeth are cutting the same amount of material. The total runout should be no more than 0.001-inch TIR.[11,12]

3-1.1.3 Tool Materials

The choice of the proper tool material for a milling cutter is not a simple matter because important relationships exist between the machine tool, the cutting tool, and the workpiece.

Conventional high-speed steel cutters (like T1, T2, M1, M2) are popular mainly because of their ready availability. They are normally used on titanium in the following instances:

(1) Low production volume of small parts
(2) Slots and form cuts
(3) Milling under conditions of insufficient rigidity
(4) End mills, form mills, narrow side-cutting slitting saws, and large radius cutters.

The T4 and T5 cobalt grades are used for high-production milling of small parts.[7] Tool life of high-speed steel cutters is low by the usual standards and quite sensitive to speed. Furthermore, some differences in the performance of high-speed steel cutters may exist between cutters of the same type and geometry, but obtained from different suppliers. This difference can be attributed to composition and/or heat treatment of the tool. High-speed cutters, therefore, should be purchased to the specifications covering the grade and appropriate heat treatment of the steel.[4]

A complete list of high-speed steels was given in Table 3-0.1.3-2.

Carbide milling cutters are especially useful for high production or extensive metal-removal operations, particularly in face-milling and slab-milling applications. Carbide milling is done extensively in the aircraft industry and is recommended whenever possible because of the higher production rates attainable.[10]

The success of carbide milling depends largely on general supervision and control. A qualified supervisor knowledgeable in carbide tooling should be responsible for the carbide milling effort. Some competitive grades of carbides were identitied in Table 3-0.1.3-1.

3-1.1.4 Feeds

Feed rates for milling titanium generally lie in the range of 0.002 to 0.008 ipt (inch per tooth) to avoid overloading the cutters, fixtures, and milling machine. Light feeds at slow speeds also help to reduce premature chipping. Delicate types of cutters and flimsy or nonrigid workpieces require smaller feeds. It is important to maintain a positive, uniform feed. Positive gear feeds without backlash are sometimes preferred over hydraulic feed mechanisms. Cutters should not dwell or stop in the cut.

Down milling (climb milling) techniques are usually used for carbide and cast alloy cutters to encourage formation of a thin chip. Conventional milling is usually more suitable for high-speed steel tools and for removing scale.[5,6]

3-1.1.5 Depth of Cut

The selection of cut depth depends on the part rigidity, the tolerances required, and the type of milling operation undertaken. For skin milling, light cuts (0.010 to 0.020 inch) seem to permit less warpage than deeper cuts (0.040 to 0.060 inch). When extrusions are being cleaned up, a 0.050-inch depth is usually allowed.[5] However, depths of cut up to 0.15 inch can be used in other situations if sufficient power is available.[12] When forging scale is present, the nose of each tooth must be kept below the scale to avoid rapid tool wear.

3-1.1.6 Cutting Speeds

Cutting speed is a very critical factor in milling titanium. Excessive speeds will cause overheating of the cutter edges and subsequent rapid tool failure. Consequently, the speeds shown in subsequent tables should not be exceeded. In fact, when a new job is being started, it is advisable to try a cutting speed in the lower portion of the recommended range for each alloy.

Sufficient flywheel-assisted spindle power should be present to maintain constant cutting speed as the cutter takes the cutting load.

3-1.1.7 Cutting Fluids

A wide variety of cutting fluids are used to reduce cutting temperatures and to inhibit galling. Sulfurized mineral oils are used extensively and are usually flood applied. Water-base cutting fluids are also widely used and are either flood or mist applied. Tool life seems to be significantly

improved (up to 300 percent) when a 5 percent barium hydroxide-water solution is used as a spray mist. However, it is mandatory to exhaust the toxic fumes from the cutting area to protect the operator, as recommended in Section 3-0.1.4.[11,14]

Some companies prefer to use the spray-mist technique for all water-base coolants because the air blows the chips free of the cutter. The mist should be applied ahead of a peripheral milling cutter (climb cutting), and at both the entrance and exit of a face-milling-type cutter. Pressurizing the fluid in an aspirator system permits better penetration to the tool-chip area, better cooling, and better chip removal, and increases tool life by a factor of two. With a flood coolant, the chips tend to accumulate behind the cutter, and occasionally are carried through the cutter. Flood application is preferred when cutting oils are used.

3-1.1.8 General Milling Techniques and Inspection

Machining titanium requires reasonably close supervision. This means that the supervisor should check all new milling setups before cutting operations begin. Thereafter, he should spot check for nicks and scratches to prevent defective parts from being processed too far.

Fixtures should hold and support the workpiece as close to the machine table as possible. The solid part of the fixture (rather than the clamps) should absorb the cutting forces. Fixtures should be rugged enough to minimize distortion and vibration.[15]

The selection of speeds, feeds, and depth of cut in any setup should take into account the rigidity of the setup, the optimum metal-removal rate/tool-life values, and the surface finish and tolerances needed on the finished part.

Milling cutters should be sharp, and should be examined for early indications of dulling. If a dull red chip starts to form, the tool should be replaced. Some companies recommend at least two cutters for a given operation. Minimum down time usually occurs when the entire cutter is replaced by a new one, rather than waiting for a dull cutter to be resharpened. The normal criterion of wear for replacing a cutter is considered to be a wearland of 0.010 inch for a carbide cutter and 0.015 inch for a high-speed steel cutter.[5]

Surface contamination may break down cutters prematurely. If this is a problem, the surface can be removed by chemical cleaning.

3-1.1.9 Face Milling Operations

3-1.1.9.0 Introduction

Face-milling operations employ the combined action of cutting edges located on the periphery and face of the cutter. The milled surface is generally at right angles to the cutter axis, and is flat except when milling to a shoulder. Face mills and end mills represent the tools used in this operation. Face mills are suitable for facing workpieces wider than 5 inches. End mills are used for facing narrow surfaces and for operations such as profiling and slotting.[16,17,18] The following tabulation shows the type of mills used in various operations.

Type Mill	Diameter, inches	Application
Face mills[a]	6 and greater	Roughing and finishing
Shell end mills	1 to 6	Facing wide surfaces
End mills	1/2 to 2	Facing narrow surfaces End milling Profiling Slotting
Slotting mills	1/2 to 2	Slots

(a) Indexable face-milling cutters using throwaway carbide inserts are available in positive or negative rakes with lead angles up to 45 degrees.

3-1.1.9.1 Face or Skin Milling

Conventional face mills of normal design are suitable for machining relatively wide, flat surfaces usually wider than 5 inches. Special face mills are also used and include the rotating insert and conical types.[33]

Diameters of face mills are important; these can exceed 6 inches, but should not be appreciably greater than the width of the cut. If a smaller diameter cutter can perform the operation and still overhang the cut by 10 percent, then a larger cutter should not be used. It is not good practice to bury the cutter in the work.[2,11]

A good surface finish and freedom from distortion are always desirable. Surface finish, in the case of milling, seems to become considerably better with decreasing feed and slightly better with increasing speed. Light cuts (0.010 to 0.020) on sheet metal seem to cause less warpage than deeper cuts (0.040 to 0.060 inch).[8]

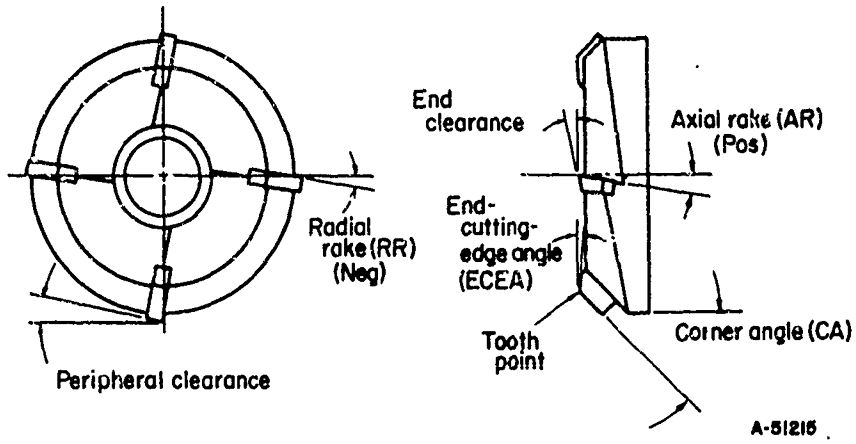
Table 3-1.1.9.1-1 contains data on feeds, speeds, depth of cut, tool design, and other variables important when titanium alloys are being forced milled. Figure 3-1.1.9.1-1 explains the tool nomenclature codes used.

TABLE 3-1.1.9.1-1. MILLING TITANIUM ALLOYS WITH HELICAL FACE MILLS[a]

Depth of Cut: 0.025 to 0.25 inch

Titanium Alloy	Alloy Condition[b]	Brinell Hardness	C-2 Carbide Tools[c]: Tool Geometry[d]	C-2 Carbide Tools[c]: Cutting Fluid[e]	C-2 Carbide Tools[c]: Cutting Speed[f], fpm: Brazed	C-2 Carbide Tools[c]: Cutting Speed[f], fpm: Throw Away	C-2 Carbide Tools[c]: Feed, ipt	High-Speed Steel Tools[c]: Tool Material	High-Speed Steel Tools[c]: Tool Geometry[d]	High-Speed Steel Tools[c]: Cutting Fluid[e]	High-Speed Steel Tools[c]: Cutting Speed[f], fpm	High-Speed Steel Tools[c]: Feed, ipt
Commercially pure	Ann.	110-170	C	1,3,5	400-530	440-585	0.004-0.008	M1, M2, M7, T1	A	1,3,5	125-175	0.003-0.008
Commercially pure	Ann.	140-200	C	1,3,5	300-400	330-440	0.004-0.006	M1, M2, M7, T1	A	1,3,5	100-140	0.003-0.006
Commercially pure	Ann.	200-275	C	1,3,5	200-300	220-310	0.004-0.006	M1, M2, M7, T1	A	1,3,5	75-110	0.003-0.006
Ti-8Al-1Mo-1V	Ann.	320-370	B, D	1,3	110-150	120-160	0.004-0.006	M3, M33, T5, T15	A, G	1,3	25-40	0.003-0.006
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	Ann.	300-340	A, B E, F	1,2,3	170-210	190-245	0.002-0.006	M2, M3, M10, M33, T5, T15	A, C, E, F	1,2,5	30-60	0.002-0.008
Ti-4Al-3Mo-1V	Ann.	300-340	A, B	1,2,3	170-210	190-245	0.002-0.006	M3, T5	A, C, F	1,4,5	40-60	0.002-0.007
	STA	375-420	B, C	1,2,4	60-100	90-115		M15, T15	A, C	6,7	20-35	
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	Ann.	310-350	A, B, C, E, F	1,3,4	100-170	190-245	0.004-0.006	M3, M33	A, C, E	1,4,5	40-50	0.002-0.006
	STA	350-400	B, C, E	1,4	80-145	120-160		T15	A, C, E	6,7	20-45	
Ti-7Al-4Mo	Ann.	320-370	B, C, E	1,3,4	110-150	120-175	0.004-0.006	M2, M3, M10, M33	A, C, E	1,4	25-60	0.004-0.007
Ti-6Al-6V-2Sn	STA	375-420	C, E	1,4	80-105	90-115		T15	C, E	1,4	25-35	
Ti-13V-11Cr-3Al	Ann.	310-350	B, C, E	1,3,4	100-125	110-145	0.003-0.006	T15, M33	C, E	4	15-35	0.004-0.007
	STA	375-440	B, C, F, E	1,4	60-80	65-90		T15, M33	C, E	4	15-25	

(a) From References (2), (3), (7), (8), (11), (14), (19)-(28).
(b) Ann. = annealed; STA = solution treated and aged.
(c) CISC designations for carbides; AISI designations for high-speed steels.
(d) See Figure 3-1.1.9.1-1 for tool angles involved.
(e) See page 3-0:67-4 for specific types. Remove all chlorinated oil residues with MEK.
(f) The lower speed in each range is used for the heavier feeds and depths of cut. Also, some companies may prefer these lower speeds for general operations, and somewhat higher speeds for numerical control machining.



Tool Geometry Code:	A	B	C	D	E	F	G	H
Axial Rake, deg	0	0	0(to +10)	+6 to -6	+10(to 0)	0 to +10	0 to +6	15
Radial Rake, deg	0(to +10)	0(to -10)	0	0 to -14	0(to +10)	0 to +10	0 to +14	0
End Relief, deg	12	12	10	6 to 12	7 to 10	7 to 12	6 to 12	12
Peripheral Relief, deg	12	12	10	6 to 12	7 to 10	7 to 12	6 to 12	12
End-Cutting Edge, deg	6(to 12)	12(to 6)	10	6 to 12	6 to 10	6 to 12	6 to 12	(a)
Corner, deg	30	30(to 45)	45	0 to 45	45	30 to 45	30(to 45)	(a)
Nose Radius, inch	0.04	0.04	0.04	0.04	0.04	0.04	0.04	(a)

(a) No data. Note: Data from references listed in Table 3-1.1.9.1-1.

FIGURE 3-1.1.9.1-1. TOOL-GEOMETRY DATA FOR FACE MILLS

3-1.1.9.2 End Milling

End milling, a form of face-milling, utilizes the cutting action of teeth on the circumferential surface and one end of a solid-type cutter. End-milling cutters are used for facing, profiling, slotting, and end-milling operations and include the standard end mills and two-lip end or slotting mills.[9] End mills should have wide flutes to permit unrestrictive chip flow. Helical-type end mills give better performance than the straight-tooth designs.[20]

In profile or pocket milling, cutters are fed gradually into the work to keep them from grabbing and breaking. Chip crowding, chip disposal, and tool deflection can be problems during this machining operation.

Pocket milling is best done with the cutter axis in a horizontal plane to avoid recutting of chips and to give better chip-removal condition.

The proper combinations of hand of helix and hand of cut should be considered to avoid deflection of the cutter in the direction of an increasing depth of cut.[9] The choice depends on the type of milling being done For example, when milling slots, where the end of the cutter is in contact with the work, the hand of the helix and the hand of the cut should be the same. This means a right-hand helix for a right-hand cut, or a left-hand helix for a left-hand cut. When profile milling, where the periphery of the cutter is doing the cutting, the opposite is true--i.e., left-hand helix for a right-hand cut and vice versa.[9]

Cutter diameter in pocket milling depends on the radius needed on the pockets. Due to an inherent lack of rigidity, end mills should be as short as practicable, and their shank diameters should equal their cutting diameters.[3]

High-speed steel cutters are normally used for end milling, slotting, and profile-milling operations.

The shank of end mills should be softer than the cutter flutes to avoid breakage between shank and flutes.[24]

Tables 3-1.1.9.2-1, 3-1.1.9.2-2, 3-1.1.9.2-3, and 3-1.1.9.2-4 provide cutting data on peripheral milling, slotting, profile milling, and pocketing with high-speed steel and solid carbide cutters. Figure 3-1.1.9.2-1 illustrates the tool

TABLE 3-1.1.9.2-1. PERIPHERAL MILLING TITANIUM ALLOYS WITH HELICAL END MILLS[a]

Depth of Cut: 0.05 to 0.25 inch

Titanium Alloy	Alloy Condition[b]	Brinell Hardness	C-2 Carbide Tools[c] (Tool Geometry - F): Cutting Speed[d], fpm	C-2 Carbide: Feed[e], ipt at Indicated Mill Diameter: 3/8 Inch	C-2 Carbide: Feed, 3/4 Inch	C-2 Carbide: Feed, 1 to 2 Inches	M-2 High-Speed Steel Tools[c] (Tool Geometry - D): Cutting Speed[d], fpm	M-2 HSS: Feed[e], ipt at Indicated Mill Diameter: 3/8 Inch	M-2 HSS: Feed, 3/4 Inch	M-2 HSS: Feed, 1 to 2 Inches
Commercially pure	Ann.	110-170	250-375	0.002	0.005-0.006	0.007-0.010	100-175	0.002-0.005	0.005-0.007	0.007-0.009
Commercially pure	Ann.	140-200	225-375	0.002	0.005-0.006	0.007-0.010	90-150	0.002-0.005	0.005-0.007	0.007-0.009
Commercially pure	Ann.	200-275	150-215	0.001-0.003	0.004-0.006	0.006-0.007	60-85	0.001-0.003	0.004-0.005	0.005-0.006
Ti-8Al-1Mo-1V	Ann.	320-370	125-175	0.001-0.003	0.004-0.006	0.006-0.007	50-70	0.001-0.003	0.004-0.005	0.005-0.006
Ti-5Al-5Sn-5Zr, Ti-5Al-2.5Sn, Ti-7Al-2Cb-1Ta	Ann.	300-340	135-200	0.001-0.003	0.004-0.006	0.006-0.007	55-80	0.001-0.003	0.004-0.005	0.005-0.006
Ti-4Al-3Mo-1V	Ann.	300-340	135-200	0.001-0.003	0.004-0.006	0.006-0.007	55-80	0.001-0.003	0.004-0.005	0.005-0.006
	STA	375-420	100-165	0.0008-0.002	0.003-0.005	0.005-0.005	40-65	0.0008-0.002	0.0015-0.004	0.003-0.004
Ti-7Al-12Zr, Ti-6Al-4V, Ti-8Mn	Ann.	310-350	125-190	0.001-0.003	0.004-0.006	0.006-0.007	50-75	0.001-0.003	0.004-0.005	0.005-0.006
	STA	350-400	100-165	0.0008-0.003	0.003-0.005	0.005-0.006	40-65	0.0003-0.003	0.003-0.004	0.004-0.005
Ti-7Al-4Mo, Ti-6Al-6V-2Sn	Ann.	320-370	125-175	0.001-0.003	0.004-0.006	0.006-0.007	50-70	0.001-0.003	0.004-0.005	0.005-0.006
	STA	375-420	100-165	0.0008-0.002	0.003-0.005	0.005-0.006	40-65	0.0008-0.002	0.0015-0.004	0.003-0.004
Ti-13V-11Cr-3Al	Ann.	310-350	50-70	0.001-0.003	0.004-0.005	0.005-0.006	50-70	0.001-0.003	0.004-0.005	0.005-0.006
	STA	375-440	30-55	0.0006-0.002	0.0015-0.003	0.003-0.005	30-55	0.0006-0.002	0.0015-0.003	0.003-0.005

(a) From Reference 23.
(b) Ann. = annealed; STA = solution treated and aged.
(c) CISC designations for carbide; AISI designations for high-speed steel. See Figure 3.1.1.9.2-1 for tool angles involved.
(d) The higher speeds correlate with higher feeds and smaller depths of cut.
(e) Lower feeds are needed for 1/8-inch end mills.

TABLE 3-1.1.9.2.-2. SLOTTING TITANIUM ALLOYS WITH HELICAL END MILLS[a]

Depth of Cut: 0.015 to 0.25 inch

Titanium Alloy	Alloy Condition[b]	Brinell Hardness	C-2 Carbide Tools[c] (Tool Geometry - E) Cutting Speed[d], fpm	C-2 Carbide Feed[e], ipt at Indicated Mill Diameter 3/8 Inch	3/4 Inch	1 to 2 Inches	M2, M10 High-Speed Steel Tools[c] (Tool Geometry - D, H) Cutting Speed[d], fpm	M2, M10 Feed[e], ipt at Indicated Mill Diameter 3/8 Inch	3/4 Inch	1 to 2 Inches
Commercially pure	Ann.	110-170	200-375	0.0015-0.002	0.003-0.004	0.005-0.006	80-150	0.0015-0.003	0.004-0.006	0.006-0.007
Commercially pure	Ann.	140-200	175-375	0.0015-0.002	0.003-0.004	0.005-0.006	70-150	0.0015-0.003	0.004-0.006	0.006-0.007
Commercially pure	Ann.	200-275	100-190	0.0007-0.003	0.003-0.006	0.005-0.008	40-75	0.0007-0.003	0.003-0.005	0.004-0.006
Ti-8Al-1Mo-1V	Ann.	320-370	75-200	0.0007-0.003	0.002-0.006	0.005-0.008	30-50	0.0007-0.003	0.003-0.005	0.004-0.006
Ti-5Al-5Sn-5Zr, Ti-5Al-2.5Sn, Ti-7Al-2Cb-1Ta	Ann.	300-340	90-175	0.0007-0.003	0.003-0.006	0.005-0.008	35-70	0.0007-0.003	0.003-0.005	0.004-0.006
Ti-4Al-3Mo-1V	Ann.	300-340	90-175	0.0007-0.003	0.003-0.006	0.005-0.008	35-70	0.0007-0.003	0.003-0.005	0.004-0.006
	STA	375-420	60-115	0.0006-0.003	0.003-0.005	0.004-0.007	25-45	0.0005-0.003	0.001-0.004	0.002-0.006
Ti-7Al-12Zr, Ti-6Al-4V, Ti-8Mn	Ann.	310-350	75-165	0.0007-0.003	0.003-0.006	0.005-0.008	30-65	0.0007-0.003	0.003-0.005	0.004-0.006
	STA	350-400	60-115	0.0006-0.003	0.003-0.005	0.004-0.007	25-45	0.0006-0.003	0.002-0.004	0.003-0.006
Ti-7Al-4Mo, Ti-6Al-6V-2Sn	Ann.	320-370	75-140	0.0007-0.003	0.003-0.006	0.005-0.008	30-55	0.0007-0.003	0.003-0.005	0.004-0.006
	STA	375-420	60-115	0.0006-0.003	0.003-0.005	0.004-0.007	25-45	0.0005-0.003	0.001-0.004	0.002-0.006
Ti-13V-11Cr-3Al	Ann.	310-350	75-140	0.0007-0.003	0.003-0.006	0.005-0.008	30-55	0.0007-0.003	0.003-0.005	0.004-0.006
	STA	375-440	60-100	0.0004-0.002	0.002-0.004	0.002-0.006	20-45	0.0004-0.002	0.001-0.003	0.002-0.005

(a) From Refs. 14, 20, 22-24.
(b) Ann. = annealed; STA = solution treated and aged.
(c) CISC designations for carbide; AISI designations for high-speed steel. See Figure 3-1.1.9.2-1. for tool angles involved.
(d) The higher speeds correlate with higher feeds and smaller depths of cut.
(e) Lower feeds are needed for 1/8-inch end mills. Feeds for the high-speed steel end mills are conservative and may be increased in some cases.

TABLE 3-1.1.9.2-3. PROFILING TITANIUM ALLOYS WITH HELICAL END MILLS[a]

Depth of Cut: 0.015 to 0.05 inch

			C-2 Carbide Tools[c] (Tool Geometry - A)				M2 and M7 High-Speed Steel Tools[c] (Tool Geometry - A)			
			Cutting Speed[d],	Feed[e], ipt at Indicated Mill Diameter			Cutting Speed[d],	Feed[e], ipt at Indicated Mill Diameter		
Titanium Alloy	Alloy Condition[b]	Brinell Hardness	fpm	1/4 Inch	1/2 Inch	3/4 Inch	fpm	1/4 Inch	1/2 Inch	3/4 Inch
Commercially pure	Ann.	110-170	325-375	0.001-0.002	0.003	0.004	125-150	0.0015-0.002	0.004	0.006
Commercially pure	Ann.	140-200	300-375	0.001-0.002	0.003	0.004	120-150	0.0015-0.002	0.004	0.006
Commercially pure	Ann.	200-275	160-190	0.001-0.002	0.002-0.003	0.005-0.006	60-75	0.001-0.0015	0.002-0.003	0.004-0.005
Ti-8Al-1Mo-1V	Ann.	320-370	45-55	0.001-0.002	0.002-0.003	0.005-0.006	45-55	0.001-0.0015	0.002-0.003	0.004-0.005
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	Ann.	300-340	140-175	0.001-0.0015	0.002-0.003	0.005-0.006	55-70	0.001-0.0015	0.002-0.003	0.004-0.005
Ti-4Al-3Mo-1V	Ann.	300-340	140-175	0.001-0.0015	0.002-0.003	0.005-0.006	55-70	0.001-0.0015	0.002-0.003	0.004-0.005
	STA	375-420	35-45	0.001-0.0015	0.002-0.003	0.004-0.006	35-45	0.001-0.0015	0.002-0.003	0.003-0.004
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	Ann.	310-350	50-65	0.001-0.0015	0.002-0.003	0.005-0.006	50-65	0.001-0.0015	0.002-0.003	0.004-0.005
	STA	350-400	35-45	0.001-0.0015	0.002-0.003	0.004-0.006	35-45	0.001-0.0015	0.002-0.003	0.003-0.004
Ti-7Al-4Mo Ti-6Al-6V-2Sn	Ann.	320-370	50-65	0.001-0.0015	0.002-0.003	0.005-0.006	45-55	0.001-0.0015	0.002-0.003	0.004-0.005
	STA	375-420	35-45	0.001-0.0015	0.002-0.003	0.004-0.006	35-45	0.001-0.0015	0.002-0.003	0.003-0.004
Ti-13V-11Cr-3Al	Ann.	310-350	45-55	0.001-0.0015	0.002-0.003	0.005-0.006	45-55	0.001-0.0015	0.002-0.003	0.004-0.005
	STA	375-440	35-45	0.0007-0.001	0.0015-0.002	0.003-0.004	35-45	0.0007-0.001	0.0015-0.002	0.002-0.003

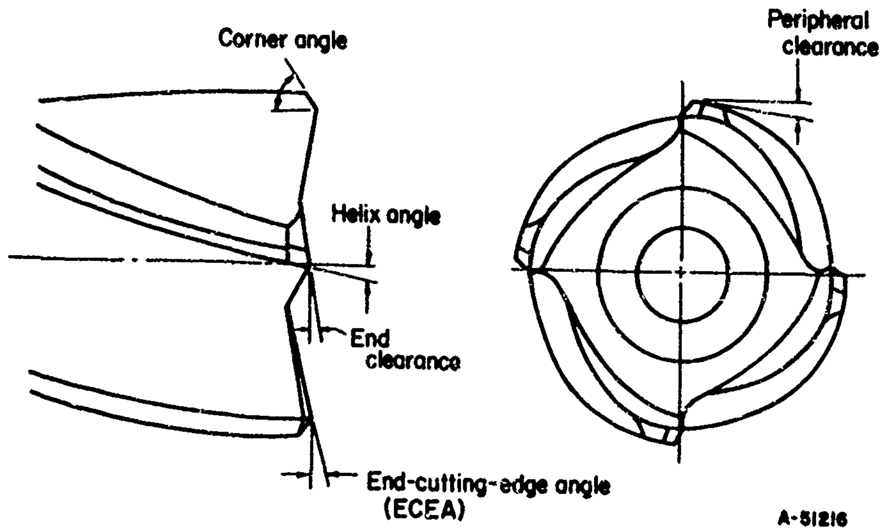
(a) From References 21, 29, and 30.
(b) Ann. = annealed; STA = solution treated and aged.
(c) CISC designations for carbide; AISI designations for high-speed steel. For Ti-13V-11Cr-3Al and titanium alloys in the heat-treated condition use T15, M33, or M41 to M44 high-speed steel compositions if high-speed steel end mills are used. See Figure 3-1.1.9.2-1 for tool angles involved.
(d) The higher speeds correlate with lower feeds and smaller depths of cut.
(e) Lower feeds are needed for 1/8-inch end mills.

TABLE 3-1.1.9.2-4. POCKET MILLING TITANIUM ALLOYS WITH HELICAL END MILLS[a]

Axial Depth of Cut: 1 inch
Radial Depth of Cut: 0.03-0.125 inch

Titanium Alloy	Alloy Condition[b]	Brinell Hardness	M-2 or M-10 High-Speed Steel Tools[c] (Tool Geometry - H) Cutting Speed[d], fpm	Feed[e], ipt At Indicated Cutting Diameter 1/2 inch	5/8 inch	3/4 inch
Ti-5Al-5Sn-5Zr	Ann.	310	40-50	0.002-0.003	--	--
Ti-5Al-2.5Sn			40-60	--	0.003-0.004	--
Ti-7Al-2Cb-1Ta			45-65	--	--	0.004-0.005
Ti-6Al-4V	STA[f]	365	25-30	0.002-0.004	--	--
			25-40	--	0.003-0.004	--
			35-45	--	--	0.004-0.005
Ti-7Al-4Mo	STA[f]	365	30-40	0.002-0.004	--	--
Ti-6Al-6V-2Sn			35-50	--	0.004	--
			40-55	--	--	0.004-0.005
Ti-13V-11Cr-3Al	STA[f]	365	10-20	0.002-0.004	--	--
			20-30	--	0.002-0.004	--
			30-40	--	--	0.004-0.005

(a) From References 20 and 22.
(b) Ann = annealed; STA = solution treated and aged.
(c) AISI designations for high-speed steel. See Figure 3-1.1.9.2-1 for tool angles involved.
(d) The higher speeds correlate with higher feeds and smaller depths of cut.
(e) Lower feeds are needed for 1/8-inch end mills. Feeds between 0.005 and 0.008 are used for 1-inch mills.
(f) Speed and feed recommendations for these heat treated alloys can be increased 30 percent when machining these alloys in the annealed condition.



Tool Geometry Code:	A	B	C	D	E	F	G	H
Helix, deg	30	45	30	30	15	30	30	30 ±3
Radial Rake, deg	10	10	10	10	0	0 to +4	10	12 ±2
End Clearance, deg	12	(a)	15	5 to 8	12	(a)	3	5 to 8(b)
Peripheral Clearance, deg	5	4 to 15	(a)	5	12	6	7 to 10	5 to 12(c)
End-Cutting Edge, deg	3	(a)	(a)	3	3	(a)	1	5 to 7(d)
Corner, deg	(a)	(a)	45 x 0.040	45 x 0.060	45 x 0.040	(a)	45 x 0.060	45 x 0.060(e)
Nose Radius, inch	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)

(a) No data. (b) See "A" of Table 3-1.1.9.2-5. (c) See "B" of Table 3-1.1.9.2-5. (d) See "C" of Table 3-1.1.9.2-5. (e) See "D" of Table 3-1.1.9.2-5.

FIGURE 3-1.1.9.2-1. TOOL-GEOMETRY DATA FOR END MILLS[7,14,20,22-24,29,30]

nomenclature and codes used. Table 3-1.1.9.2-5 contains additional data on end mills.

TABLE 3-1.1.9.2-5. TOOL GEOMETRY VARIATIONS FOR END MILLS[22]

A. End Clearance Angles

Diameter, inch	2 and 3 Flutes Primary Clearance, degrees	4 Flutes and Over, Primary Clearance, degrees	All Mills Secondary Clearance, degrees
Under 5/8	8	6	15
5/8 and over	7	5	12

Tolerance: Basic ±1°

C. End-Cutting Edge Angles

Diameter, inch	ECEA, degrees
Under 3/8	7
3/8 thru 3/4	6
Over 3/4	5

Tolerance: Basic ±1°
ECEA also defined as dish.

B. Peripheral Clearance Angles

Diameter, inch	Primary Clearance, degrees	Offset, inch	Secondary Clearance, degrees	Offset, inch	Primary Land Width, inch
1/8	12	0.013	20	0.022	0.006
3/16	12	0.020	20	0.033	0.006
1/4	10	0.022	18	0.042	0.007
5/16	10	0.028	18	0.050	0.007
3/8	9	0.039	16	0.053	0.008
7/16	9	0.035	16	0.062	0.008
1/2	8	0.035	14	0.062	0.009
9/16	8	0.040	14	0.069	0.009
5/8	8	0.044	14	0.077	0.010
11/16	7	0.043	12	0.073	0.010
3/4	7	0.046	12	0.079	0.010
13/16	7	0.050	12	0.086	0.012
7/8	7	0.054	12	0.092	0.012
15/16	6	0.050	10	0.083	0.014
1	6	0.053	10	0.088	0.014
11/4	6	0.066	10	0.110	0.016
11/2	6	0.079	10	0.132	0.016
13/4	5	0.077	10	0.154	0.018
2	5	0.083	10	0.176	0.018

Tolerance

Diameter, inch	Primary, degrees	Secondary, degrees	Land Width, inch
Under 1/2	Basic $^{+2}_{-0}$	Basic ±2	$^{+0.003}_{-0.000}$
1/2 and over	Basic $^{+2}_{-0}$	Basic ±2	$^{+0.004}_{-0.000}$

D. Corner Angle Clearance and Chamfer

Diameter, inch	Primary Clearance, degrees	Secondary Clearance, degrees	Primary Land Width, inch	Chamfer
1/8 thru 5/16	12	24	0.015	45° x 0.015
3/8 thru 5/8	9	22	0.025	45° x 0.030
11/16 thru 1	6	20	0.035	45° x 0.060
Over 1	6	18	0.050	45° x 0.060

Tolerance: Cl. Angle; Basic ±1°; Land Width Basic, $^{+0.006}_{-0.000}$, Chamfer, ±1° ±0.005

3-1.1.10 Peripheral Milling Operations

3-1.1.10.0 Introduction

Peripheral milling operations utilize the cutting action of teeth located on the periphery of the cutter body. Arbor-mounted cutters used for such operations include plain mills, helical mills, slab mills, form-relieved cutters, formed-relieved cutters, side mills, and slotting cutters.

It should be noted, however, that face mills are usually more efficient in removing metal from flat surfaces and produce them more accurately than plain milling cutters do. Faster feed rates are also possible with face mills because they are more rugged. In addition, the complicated supports usually required for arbor-mounted cutters are unnecessary when face mills are employed.

3-1.1.10.1 Spar or Slab Milling

Spar or slab milling is used to bring extrusions into aircraft tolerance and to provide a good surface finish. The operation can be performed on a heavy-duty fixed-bed mill like the Sundstrand "Rigidmil". Large bed mills, however, may have adequate feed ranges.

Spars and similar sections, being relatively long and thin, require special considerations. As-received extrusions may need straightening before machining, since extrusion straightness tolerances exceed mill fixture and part tolerances.[5]

Rigid setups are necessary, but spar extrusions should not be forced into a fixture. Spars may be straightened mechanically if the distortion is not too severe. Otherwise, they should be hot straightened in fixtures.

When arbor-mounted cutters are being used, the arbor should be of the largest possible diameter, and should be supported on each side of the cutter with over-arm supports. Furthermore, the arbor should have just the proper length required for the number of cutters mounted and the arbor support employed. Arbor overhang beyond the outer support should be avoided because it is conducive to chatter and vibration. Finally, cutters should be mounted as close to the column face of the milling machine as the work will permit.[9]

Slab milling cutters should be mounted so that the cutting forces will be absorbed by the spindle of the machine. This is accomplished by using cutters with a left-hand helix for a right-hand cut, and vice versa. When two milling cutters are used end-to-end on the arbor, cutters having helixes of opposite hand to the cut involved should be used. This setup neutralizes the cutting forces that tend to push the cutters away from the arbor.

Carbide cutters are preferred for spar milling because of the higher production rates attainable--except under conditions where the inherent brittleness of the carbide precludes its use. Helical cutters are recommended. They provide wider and thinner chips than do the corresponding straight-tooth types. In slab milling, six cutting edges per inch diameter allows heavier feeds and longer tool lives than the conventional three cutting edges per inch diameter.[14]

The unit feeds range between 0.004 to 0.012 ipt, depending on the finish desired. However, too light a feed can produce red-hot chips, which can cause a fire hazard.

When extrusions are being clean up, only about 0.05-inch depth of cut can be taken in order to reduce material costs. Hence, for long parts, the feed/speed combination, which gives the most economical metal removal based on machines available and cutting tool inventory, should be used.

Table 3-1.1.10.1-1 gives machining data used for slab milling commercially pure titanium and several titanium alloys.

3-1.2 TURNING AND BORING OPERATIONS

Turning, facing, and boring operations on titanium are essentially the same, and no unusual difficulties are experienced with any of them. They give less trouble than milling, especially when cutting is continuous rather than intermittent. The same speeds used for turning can be used for boring and facing cuts. However, in most cases, the depths of cut and feeds will have to be reduced during boring because of an inherent lack of rigidity of the operation.[4]

The problems to be minimized in turning-type operations include high tool-tip temperatures, and the galling and abrasive properties of titanium toward tool materials. They can be avoided by following the precautions listed in Section 3-0.1.2 and the suggestions given below. The conditions identified in this section for turning should be suitable for boring with single-point tools.

3-1.2.1 Lathes

A modern lathe in good condition provides production rates of five to ten times the rates possible with older machines. Vibration and lack of rigidity are common problems with older equipment. Furthermore, the over-all range of spindle speeds available on many of the existing lathes is not broad enough to cover some of the lower speeds needed for titanium.

Lathes should have either a variable-speed drive for the spindle, or the spindle gear train

TABLE 3-1.1.10.1-1. SLAB MILLING TITANIUM ALLOYS WITH HIGH-SPEED STEEL PERIPHERAL MILLS[a]

Titanium Alloy	Alloy Condition[b]	Brinell Hardness	Rough Machining Depth of Cut: 0.150 inch		Finish Machining Depth of Cut: 0.025 inch		AISI Type High-Speed Steel
			Cutting Speed, fpm	Feed, ipt	Cutting Speed, fpm	Feed, ipt	
Commercially pure	Ann.	110-170	110	0.008	153	0.004	M2, M7
Commercially pure	Ann.	140-200	90	0.006	125	0.004	M2, M7
Commercially pure	Ann.	200-275	65	0.006	100	0.004	M2, M7
Ti-8Al-1Mo-1V	Ann.	320-370	25	0.006	35	0.004	T15, M33
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	Ann.	300-340	45	0.006	55	0.004	T15, M33
Ti-4Al-3Mo-1V	Ann. STA	300-340 375-420	45 20	0.006 0.006	55 30	0.004 0.004	T15, M33
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	Ann. STA	310-350 350-400	35 30	0.006 0.006	45 40	0.004 0.004	T15, M33
Ti-7Al-4Mo Ti-6Al-6V-2Sn	Ann. STA	320-370 375-420	25 20	0.006 0.006	35 30	0.004 0.004	T15, M33
Ti-13V-11Cr-3Al	Ann. STA	310-350 375-440	20 20	0.006 0.006	30 25	0.004 0.004	T15, M33

(a) From Reference (21).
(b) Ann. = annealed; STA = solution treated and aged.

should have a geometric progression of 1.2 or less in order to provide speed steps of 20 percent or less for more precise speed selections. The trend in new lathes is toward variable-speed drives. Rigidity, backlash elimination, dimensional accuracy, rapid indexing of tools, and flexibility are additional features that are being emphasized.[19]

The application of numerical control in turning is rapidly spreading. On lathes equipped with tracer control or numerical control, variable-speed and feed features can be added so that the speed and feed can be optimized during contouring operations.[19]

Lathes with 10-horsepower ratings should be ample for most turning operations. Workpieces ranging between 1 inch and 10 inches in diameter can be turned on a standard or heavy-duty 1610 engine lathe. These lathes have a range of spindle speeds that almost meet the requirements previously described.[19]

3-1.2.2 Cutting Tools, Tool Design, and Tool Quality

Standard lathe tools are used for turning titanium; they are available in a variety of shapes, sizes, tool angles, and tool materials. High-speed steel, carbide, and cast alloy tools can be used.[8]

Tool angles are important for controlling chip flow, minimizing smearing or chipping, and maximizing heat dissipation. The rake angles and the side-cutting-edge angle determine the angle of inclination and chip flow. Relief angles, together with the rake angles, control chipping and smearing.

Positive, zero, or negative rake angles can be used, depending on the alloy, heat-treated condition, the tool material, and machining operation. The side rake is the important angle, positive rakes being best for finish turning and high-speed steel tools, and negative rakes for carbide tools at heavier feeds.[8,11,12]

The side-cutting edge angle influences the cutting temperature near the cutting zone. Larger angles reduce cutting pressure and present longer tool edges. The reduced pressure minimizes heat formation; longer cutting edges allow a greater amount of heat dissipation. Hence, higher values of the side-cutting edge angle generally permit greater feeds and speeds--unless chipping occurs as the cutting load is applied or removed.[8,11]

Relief angles between 5 and 12 degrees can be used on titanium. Angles less than 5 degrees encourage smearing of titanium on the flank of the tool. Relief angles around 10 degrees are better, although some chipping can occur.[8,11]

Chip breaking devices should be used for good chip control.[4]

Figure 3.1.2.2-1 explains the nomenclature used for single-point cutting tools. Table 3-1.2.2-1 shows the tool geometries used when turning titanium. Cutting tools should be carefully ground and finished before use. Normally, this means that tool surfaces over which chips pass should possess a good finish, with the direction of finishing corresponding to the chip-flow direction. A rough surface can cause a properly designed tool to deteriorate rapidly. The life of a carbide tool can be extended if the sharp cutting edge is slightly relieved by honing.[1,8]

3-1.2.3 Tool Materials

High-speed steel, cast alloy, and cemented carbide cutting tools are suitable for lathe turning titanium. Ceramic tools have not proved successful for titanium machining.[31]

Experience indicates that high-speed steel tools are best suited for form cutting, heavy plunge cuts, interrupted cutting, and minimum rigid setup conditions. Carbide tools are normally used for continuous cutting situations, high-production items, extensive metal-removal operations, and scale removal. Nonferrous cast alloy tools are suitable for severe plunge cuts, machining to dead center, and producing narrow grooves.

High-speed steel and cast alloy tools should be ground on a tool grinder to the tool geometry needed. The same is true for carbide tools; however, off-the-shelf brazed and throwaway carbide tools may fit the rake, lead, and relief angle requirements and are convenient to use.

Brazed tools may be purchased in standard sizes and styles, as shown in Table 3-1.2.3.1, or they can be made up in the shop. However, the performance of mechanically clamped inserts is at least as good as that of brazed tools, and consequently are recommended because of their lower cost per cutting edge.

Throwaway carbide inserts are designed to be held mechanically in either positive- or negative-rake tool holders of various styles and shank sizes. Information and data on available tool holders are given in manufacturers' brochures. The general coding system for mechanical tool holders is explained in Table 3-1.2.3-2. The tool geometries available for solid-base tool holders and suitable for titanium are shown in Table 3-1.2.3-3.

Substantial reductions in costs are claimed by users of throwaway tooling. Factors contributing to this saving include:

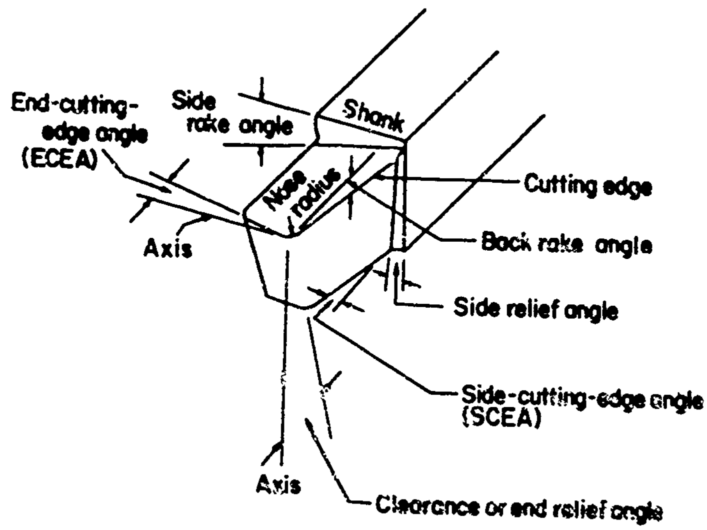


FIGURE 3-1. 2. 2-1. TOOL-GEOMETRY COMENCLATURE

TABLE 3-1. 2. 2-1. TOOL-GEOMETRY DATA (7)

	Tool Angles and Nose Radius for Indicated Tool-Geometry Code								
	A	B	C	D	E	F	G	H	I
Back Rake, degrees	-5	+5 to -5	+5 to -5	0	0	0 to +5	0 to +10	+6 to +10	+5 to +15
Side Rake, degrees	-5	+6 to 0 0 to -6	+5	5 or 6	15	+5 to +15	0 to +10	0 to +15	+10 to +20
End Relief, degrees	5	5-10	8-10	5	5	5-7	6-8	6-10	5-8
Side Relief, degrees	5	5-10	8-10	5	5	5-7	6-8	6-10	5-8
End-Cutting Edges, degrees	15-45	6-15	5-10	15 or 5	10 to 15	5-7	5-10	5-15	5-15
Side-Cutting Edge (Lead), degrees	15-45	5-20	0-45	15	15 to 45	15-20	0-30	0-45	0-30
Nose Radius, inch	1/32-3/64	03-04	03-04	3/64	3/64	02-03		03-04	01-03

(1) Reduced tool-grinding costs
(2) Reduced tool-changing costs
(3) Reduced scrap
(4) Increased use of harder carbides for longer tool life or increased metal-removal rates
(5) Savings through tool standardization
(6) Maximum carbide utilization per tool dollar.

Disposable-type carbide (C-2) inserts in heavy-duty negative rake tool holders provide maximum metal removal at minimum cost in turning.

Carbide cutting tools are the most sensitive to chipping and hence require "over-powered", vibration-free lathes, as well as more-rigid tool-work setups. If these conditions cannot be met, then high-speed steels must be used.

3-1. 2. 4 Feeds

The three cardinal rules for feeding practices when turning titanium are:

(1) Always use constant, positive feeds
(2) Avoid dwelling in the cut
(3) Never stop or slow up in the cut.

TABLE 3-1.2.3-1. TOOL GEOMETRIES OF BRAZED CARBIDE TOOLS[7]

Tool Geometry	Style of Tool A	B	C	D	E
Back rake	0	0	0	0	0
Side rake	+7	+7	0	0	0
End relief	7	7	7	7	7
Side relief	7	7	7	7	7
ECEA	8	15	--	50	60
SCEA	0	15	--	40	30

TABLE 3-1.2.3-2. EXPLANATION OF GENERAL CODING SYSTEM FOR MECHANICAL TOOL HOLDERS[7]

Company Identification	Shape of Insert	Lead Angle	Rake Angle	Type Cut
(a)	T	B	(b)	R or L
(a)	R	A	(b)	R or L
(a)	P	A	(b)	R or L
(a)	S	B	(b)	R or L
(a)	L	B	(b)	R or L
	T	A	T	R

Shape of Insert	Lead Angle or Tool Style	Type Cut
T = triangle	A = 0-degree turning	R = right hand
R = round	B = 15-degree lead	L = left hand
P = parallelogram	D = 30-degree lead	N = neutral
S = square	E = 45-degree lead	
L = rectangle	F = facing	
	G = 0-degree offset turning	

(a) Some producers place a letter here for company identification.
(b) Some companies use the letter "T" for negative rake, "P" for positive rake, and sometimes add "S" to indicate "solid-base" holders. For example, a TATR designation denotes a tool holder for a triangular insert mounted in such a way to give a 0-degree lead angle, and a 5-degree negative rake. The "R" denotes a right-hand cut.

The metal removal rate and surface finish requirements will determine the amount of feed to be taken; heavy feeds for higher metal-removal rates, light feeds for better surface finishes.[8]

3-1.2.5 Depth of Cut

The choice of cut depth will depend on the amount of metal to be removed and the metal-removal rate desired. In removing scale, the tool should get under the scale and cut at least 0.020 inch deeper than the tool radius.[4] For rough cuts, the nose of the tool should get below any hard skin or oxide remaining from previous processing operations. In finish turning, light cuts should be used for the best finish and the closest tolerances.[8,11]

3-1.2.6 Cutting Speed

Tool life when turning titanium is more sensitive to cutting speed than to any other machining variable. However, and fortunately for titanium, high speeds are not necessary for producing good finishes. Hence, relatively low cutting speeds compared to those associated with conventional metals are used to obtain reasonable tool life for titanium.[1,8]

3-1.2.7 Cutting Fluids

Cutting fluids are almost always used during turning and boring operations to cool the tool and to aid in chip disposal. Dry cutting is done in only a very few instances, usually where chip contamination is objectionable. Dry cutting is not recommended for semifinishing and finishing operations on titanium.

Water-base coolants are the most satisfactory cutting fluids used for turning titanium. Specifically, a 5 percent solution of sodium nitrate in water gives the best results, while a 1:20 soluble-oil-in-water emulsion is second best. Sulfurized oils may be used at low cutting speeds, but precautions must be taken to avoid possible fires. A full, steady flow of cutting fluid should be maintained at the cutting site.

3-1.2.8 Control and Inspection

When setting up a turning operation, the work should be firmly chucked in the collet of the spindle and supported by the tail stock with a live center. The tool should be held firmly in a flat-base holder and set to cut on dead center. Machining should be done as closely as possible to the spindle for minimum work overhang. A steady rest or follow rest should be used to add rigidity to slender parts.

During machining, chips should be expelled from the work area as promptly as possible, particularly during boring. Chips lying on the surface tend to produce chatter and poor surface finishes.

The tool should be examined frequently for nicks or worn flanks. These defects promote galling, increase cutting temperature, accelerate tool wear, and increase residual stresses in the machined surface.

Arbitrary tool-changing schedules are desirable. Usually, this means replacing carbide tools after 0.015-inch wearland in rough turning, and 0.010-inch wearland in finish turning. High-speed steel tools are replaced after a wearland of 0.030 inch is developed. When periodic interruptions are made in a machining operation, before the maximum wearland occurs, any welded-on metal, nicks, and crevices should be removed by honing.[1,8,11,20,22,23,32]

TABLE 3-1.2.3-3. TOOL GEOMETRIES OF SOLID-BASE TOOL HOLDERS FOR THROWAWAY INSERTS[7]

Negative Rake Tools				Positive Rake Tools			
Back rake angle: 5 degrees Side-rake angle: 5 degrees End-relief angle: 5 degrees Side-relief angle: 5 degrees				Back-rake angle: 0 degrees Side-rake angle: 5 degrees End-relief angle: 5 degrees Side-relief angle: 5 degrees			
Tool Holder Style[a]	Type Insert[a]	ECEA[b], degrees	SCEA[c], degrees	Tool Holder Style[a]	Type Insert[a]	ECEA[b], degrees	SCEA[c], degrees
[illegible]	T	5	0	A	T	3	0
	T	3	0	A	T	5	0
[illegible]	R	8	0	--	--	--	--
B	T	23	15	B	T	23	15
B	T	18	15	B	S	15	15
B	S	15	15	B	T	20	15
B	T	20	15	--	--	--	--
D	T	35	30	D	T	35	30
E	S	45	45	--	--	--	--
F	T	0	0	F	T	0	0
F	S	15	0	F	S	15	0
G	T	3	0	G	T	3	0

(a) See Table 3-1.2.3-2 for explanations under "Lead Angle or Tool Style".
(b) End-cutting-edge angle.
(c) Side-cutting-edge angle.

Sharp edges of turned titanium surfaces are potential sources of failure. Hence, they should be "broken" with a wet file or wet emery. This operation should not be done dry or with oil because of a potential fire hazard.[1]

After certain turning operations, parts may require stress relieving.[1] The following treatments are suggested:

Anneal after rough machining
Stress relieve thin-wall parts after semifinish operations
Stress relieve all finished parts.

Data on speeds, feeds, and depths of cut for carbides and high-speed steel tools are shown in Tables 3-1.2.8-1 and 3-1.2.8-2.

DRILLING OPERATIONS

[illegible] Introduction

[illegible] techniques [illegible] for other materials. Thin [illegible] are likely to fold [illegible] the drill. Also, the usual [illegible] accentuated by high [illegible] temperatures and pressures, produces [illegible] wear. Out-of-round holes, tapered holes, or smeared holes are the apparent results, with subsequent tap breakage if the holes are to be threaded.

These problems can be minimized by:

(1) Using short, sharp drills
(2) Supplying cutting fluids to the cutting zone
(3) Employing low speeds and positive feeds
(4) Supplying solid support to the workpiece, especially on the exit side of the drilled hole, where burrs otherwise would form.

3-1.3.1 Machine Tools for Drilling

Drilling machines must be sturdy and rigid enough to withstand the thrust and torque forces built up during the cutting. Hence, the spindle overhang should be no greater than necessary for a given operation. In addition, excessive clearances in spindle bearings cannot be tolerated. The radial and thrust bearings should be good enough to minimize runout and end play. Finally, the feed mechanism should be free of backlash in order to reduce the strain on the drill when it breaks through the workpiece.[7,8,35,36]

Machines for drilling operations are made

TABLE 3-1.2.8-1. FINISH TURNING OF TITANIUM ALLOYS[a]

Depth of Cut: 0.025 to 0.10 inch
Feed: 0.005 to 0.010 ipr

Titanium Alloy	Alloy Condition[b]	C-3, C-2 Carbide Tools[c] Tool Geometry[d]	Cutting Speed[e], ipm Brazed Tools	Cutting Speed[e], ipm Throwaway	High-Speed Steel Tools[c] AISI Steels	Tool Geometry[d]	Cutting Speed[e], ipm
Commercially pure (110-170 Bhn)	Ann.	A, D	450-500	500-550	T15, M3	D	200-250
Commercially pure (140-200 Bhn)	Ann.	D	375-425	425-475	T15, M3	D	160-180
Commercially pure (200-275 Bhn)	Ann.	D	250-275	310-350	T15, M3	D	100-110
Ti-8Al-1Mo-1V	Ann.	A, D	90-155	165-185	M3, T5, T15	D, F, G	20-50
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	Ann.	A, B, D	165-215	220-250	M5 T5 T15	D, F	40-80
Ti-4Al-3Mo-1V	Ann.	A	165-215	225-250	M3, T5, T15	D, F	45-80
	STA	A	100-120	120-150		F	40-50
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	Ann.	A, D, G	150-170	180-210	M3, T5, T15	D, F	45-70
	STA	A, D	120-145	160-185	M3, T15	D, F	25-65
Ti-7Al-4Mo Ti-6Al-6V-2Sn	Ann.	A	130-155	165-185	M3, T15	D, F	50-60
	STA	A	100-120	120-150	T15	E, F	30-50
Ti-13V-11Cr-3Al	Ann.	A	100-125	120-150	M3, T15	D, F	25-35
	STA	A	80-100	100-120	T15	E, F	20-35

(a) Refs. (8, 11, 23, 33, 34).
(b) Ann. = annealed; STA = solution treated and aged.
(c) CISC designations used for carbides; AISI designations for high-speed steels.
(d) See Table 3-1.? 2-1 for tool angles involved.
(e) Higher speeds are associated with lower feeds and lower depths of cut.

TABLE 3-1.2.8-2. ROUGH TURNING OF TITANIUM ALLOYS[a]

Depth of Cut: 0.10 to 0.25 inch
Feed: 0.010 to 0.015 ipr

Titanium Alloy	Alloy Condition[b]	C-2 Carbide Tools[c] Tool Geometry[d]	Cutting Speed[e], fpm Brazed Tools	Throwaway	High-Speed Steel Tools[c] Tool Material	Tool Geometry[d]	Cutting Speed[e], ipm
Commercially pure (110-170 Bhn)	Ann.	A, F, G	400-450	450-500	T15, M3	D	175-200
Commercially pure (140-200 Bhn)	Ann.	A	325-375	375-425	T15, M3	D	140-160
Commercially pure (200-275 Bhn)	Ann.	A	225-250	275-310	T15, M3	D	90-100
Ti-8Al-1Mo-1V	Ann.	A, F, G	70-140	150-200	M3, T5, T15	B, E, F, G	20-60
Ti-5Al-5Sn-5Zr, Ti-5Al-2.5Sn, Ti-7Al-2Cb-1Ta	Ann.	A, F, G, H	140-180	140-220	M3, T5, T15	B, E, K, F	30-80
Ti-4Al-3Mo-1V	Ann.	A	150-180	185-220	M3, T5, T15	B	60-80
	STA	A	80-100	100-120	T15	E	30-40
Ti-7Al-12Zr, Ti-6Al-4V, Ti-8Mn	Ann.	A, F, G, I	140-150	180-200	M3, T5, T15	B, E, L	35-70
	STA	A, F, G	100-120	150-160	M3, T5	B, E	30-55
Ti-7Al-4Mo, Ti-6Al-6V-2Sn	Ann.	A	110-130	150-165	M3, T15	B, F	40-60
	STA[f]	A	80-120	100-120	T15	C, E, F	25-40
Ti-13V-11Cr-3Al	Ann.	A	80-100	100-120	M3, T15	B, F	20-25
	STA[f]	A	60-100	80-100	T15	D, F	20-25

(a) Refs. (8, 11, 23, 33, 34).
(b) Ann. = annealed; STA = solution treated and aged.
(c) CICS designations used for carbides; AISI designations for high-speed steels.
(d) See Table 3-1.2.2-1 for tool angles involved.
(e) Higher speeds are associated with lower feeds and lower depths of cut.
(f) 0.010 ipr max.

in many different types and sizes. Size or capacity is generally expressed either in terms of the largest diameter disc, the center of which is to be drilled; or in horsepower. Heavy-duty machines are exceptions. They are specified as the distance from the supporting column to the centerline of the chuck. The horsepower rating is that usually needed to drill cast iron with the maximum drill diameter.[36] Suitable sizes of machines for drilling titanium include:

(1) Upright Drill No. 3 or No. 4
(2) Upright Drill, Production: 21 inch, Heavy Duty, 5 HP
(3) Upright Drill, Production: 24 inch, Heavy Duty, 7-1/2 HP
(4) Upright Drill, Production: 28 inch, Heavy Duty, 10 HP.

Industry also has requirements for drilling parts at assembly locations. These needs are fulfilled by portable power-feed, air drilling machines. Modern units incorporate positive mechanical-feed mechanism, depth control, and automatic return. Some are self-supporting and self-indexing. Slow-speed, high-torque drill motors are needed. Spindle speeds between 230 and 550 rpm at 90 psi air pressure seem appropriate for high-speed drills, while speeds up to 1600 rpm have been used for carbide drills. Thrusts between 320 and 1000 pounds are available on some portable drilling machines.

Typical portable air-feed drill units include the Keller K-Matic, the (Keller Airfeedrill), Winslow Spacematic, and the Quackenbush designs.[35, 37,38]

The Keller K-Matic incorporates a positive, mechanical-feed mechanism, a depth-control device, and an automatic return provision. Drilling tests with this design indicate that Class I hole tolerances as low as +0.002 to -0.001 can be held in a drill-ream operation.[35]

The Keller Airfeedrill utilizes a variable pneumatic feed. The air feed can be adjusted to give feeds suitable for titanium. Class I hole tolerances also can be held.[35]

The Winslow Spacematic is a self-supporting, self-indexing unit capable of drilling and countersinking in one operation. The feed rates are within those prescribed for titanium, and a ±0.002/0.001 tolerance can be held.[35]

Quackenbush portable drilling machines also can be used. One style is a 500-rpm pneumatic-powered unit with a positive mechanical-feed mechanism capable of providing 0.001 ipr feed.[37]

3-1.3.2 Drills and Drill Design

The choice of drills depends on the drilling operation undertaken. Heavy-duty, stub-type screw-machine drills instead of jobbers-length drills are recommended for drilling operations on workpieces other than sheet. For deep-hole drilling, oil-feeding drills, or a series of short drills of various lengths, may be employed in sequence. Drill jigs and bushings are used whenever added rigidity is needed.[2,11,39]

Aircraft drills like NAS 907 Types C, D, and E are usually used on sheet metal. The NAS 907, Type B drill can be used where the Type C drill might be too short because of bushing length or hole depth.[7,35,37]

Large flutes reduce the tendency for chips to clog. The length of the drill should be kept as short as feasible, not much longer than the intended hole, to increase columnar rigidity and decrease torsional vibration, which causes chatter and chipping.[6,7,11,12,39]

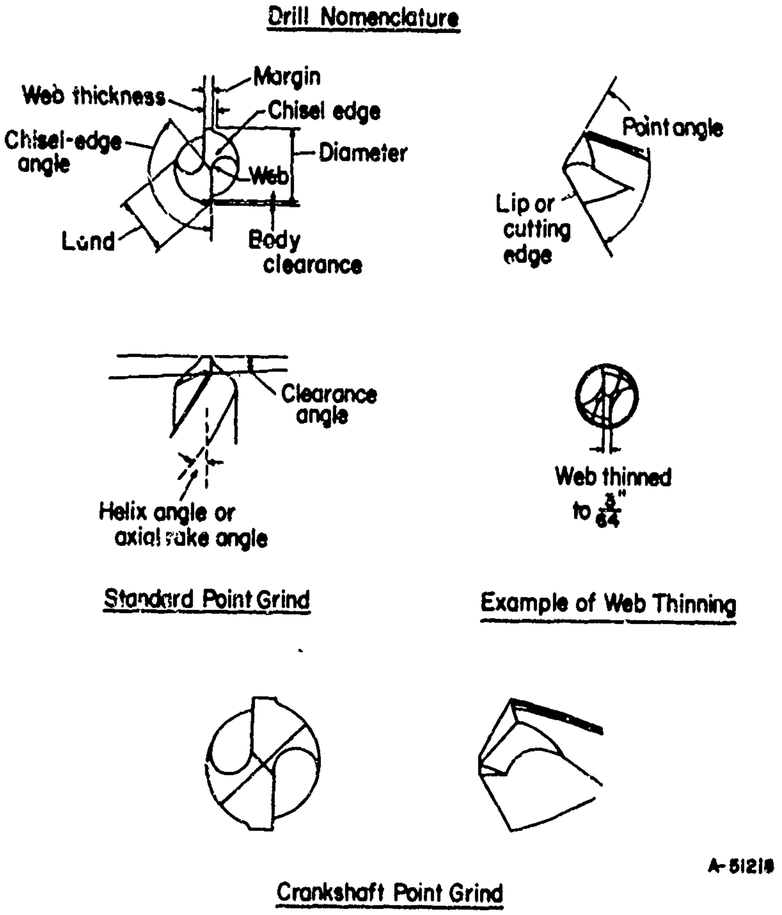
Drills having conventional drill geometry and special point grinds are used. This means a normal helix of around 29 degrees, just enough relief to prevent rubbing and pick-up, a thinned web to reduce drilling pressure, a correct point angle with its apex held accurately to the center line of the drill, and cutting lips of the same slope and of equal length. Special point grinds include crankshaft, notch-type drills, and split points with positive rake notching.[8-11]

Relief angles are of extreme importance to drill life. Small angles tend to cause excessive pickup of titanium, while excessively large angles will weaken the cutting edge. Relief angles between 7 and 12 degrees have been used by different investigators.[?,7,11,12,40]

The web is often thinned to reduce drilling pressure.[4] However, when doing so, the effective rake angle should not be altered.[7,11,12]

Point angles have a marked effect on drill life. The choice of 90, 118, or 135 degrees will depend on the feed, drill size, and the workpiece. Hence, it is advisable to try all three angles to find which is best suited for the job. Generally, blunt points (135 or 140 degrees) are superior on small-size drills (No. 40 to No. 31) and on sheet metal, while 118 degrees, 90 degrees, or the double angle (140 degrees or 118 degrees + 90-degree chamfer) seem best on larger sizes and bar stock.[7,11,40]

Figures 3-1.3.2-1 and 3-1.3.2-2 illustrate typical nomenclatures and data for standard and NAS 907-type drills. Table 3-1.3.2-1 shows some drill specifications used in the aircraft industry.[22]



Drill Element	Drill Geometry Code X	Y	Z
Drill diameter, inch	<1/8	1/8 - 1/4	1/4 and greater
Helix angle, degrees	29	29	29
Clearance angle, degrees	7 to 12	7 to 12	7 to 12
Point angle, degrees	135	118,135	118; 90 or double angle
Type point		Crankshaft (split)	

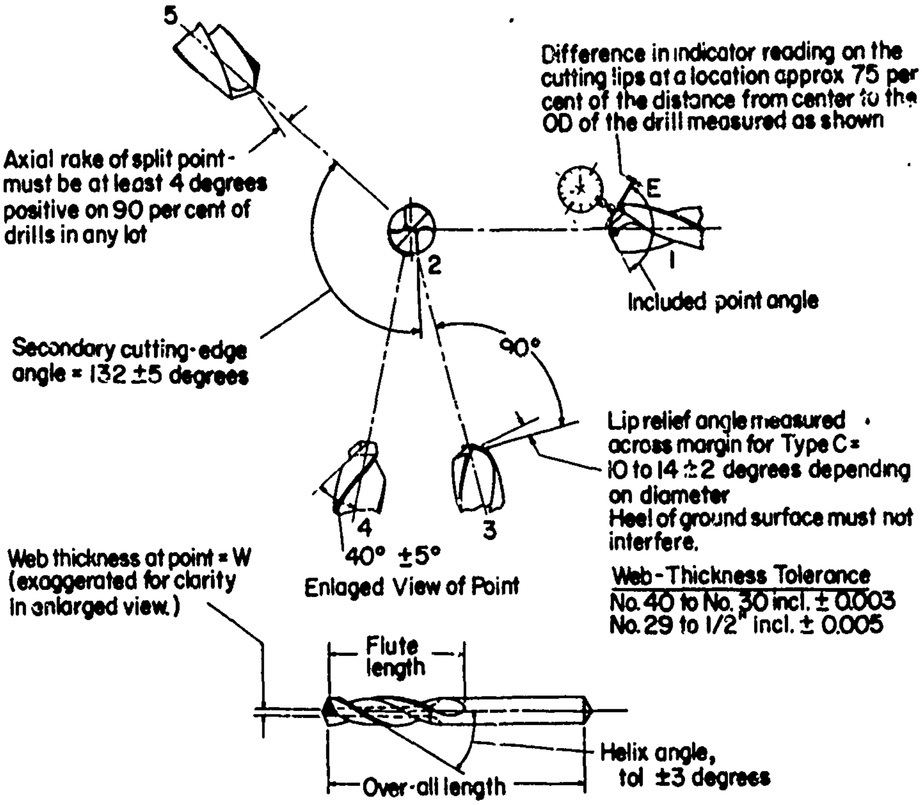
FIGURE 3-1.3.2-1. DRILL NOMENCLATURE AND TOOL ANGLES USED.

The geometry of drills should conform to recommendations. If necessary, drills should be reground accurately on a drill grinder, and the point angle, relief angle, and web thickness rechecked (Refs. (13), (43). Drills should never be sharpened by hand.[2,35]

The apex of the point angle should be held accurately to the center line of the drill, and the cutting lips should have the same slope. This combination avoids uneven chip formation, drill deflection, and oversized holes.[41]

When dull drills are reconditioned, resharpening the point alone is not always adequate. The entire drill should be reconditioned to ensure conformance with recommended drill geometry.

Machine-ground points with fine finishes give the best tool life. A surface treatment such as chromium plating or a black oxide coating of the flutes may minimize welding of chips to the flutes.[4]



Drill Elements	Drill Geometry Code C	D	B	E
Notch rake angle, degrees	4 to 7	20	4 to 7	10
Helix angle, degrees	23 to 30	28 to 32	23 to 30	12
Clearance angle, degrees	10 to 14	6 to 9	10 to 14	6 to 9
Point angle, degrees	118 ± 5	135 ± 5	135 ± 5	135 ± 5
Type point	P-5	P-1	P-3	P-2
NAS 907 drill types	C	D	B	E
Drilling application	Sheet	Hand-drilling sheet	Fixed feed	Fixed feed (dry)

FIGURE 3-1.3.2-2. DRILL NOMENCLATURE AND GEOMETRY FOR NAS 907 AIRCRAFT DRILLS (TYPE C ILLUSTRATED).

3-1.3.3 Drill Materials

Conventional molybdenum-tungsten high-speed steel drills are usually used in production. Cobalt high-speed steels can be used and are said to give up to 50 percent more tool life. However, their costs are 1-1/2 to 2 times higher than standard high-speed steels. Table 3-1.3.3-1 indicated the drilling applications for various AISI grades of high-speed steel.[7]

3-1.3.4 Feeds

The philosophy of drilling titanium is to keep the drill cutting. Never allow the drill to ride in the hole without cutting metal. The best technique is to utilize a positive mechanical feed.[4] Even assembly drilling of sheet should be done with portable power drills having positive feed arrangements. Hand drilling can be done only if sufficient thrust can be applied to insure a heavy chip

TABLE 3-1.3.2-1. SOME SPECIFICATIONS FOR DRILLS USED ON TITANIUM ALLOYS[22]

Drill diameter, inch	0.098	0.1285	0.1590	0.1850	0.1935	0.246	0.250
Overall length, inch	1-5/8	1-15/16	2-1/8	2-3/16	2-1/4	2-1/2	2-1/2
Flute length, inch	5/8	1-5/16	1-1/8	1-3/16	1-1/4	1-1/2	1-3/8
Helix angle, degrees	28 ± 2	28 ± 2	30 ± 2	30 ± 2	30 ± 2	30 ± 2	30 ± 2
Lip relief angle, degrees	7 to 10	7 to 10	12 ± 2	12 ± 2	12 ± 2	12 ± 2	12 ± 2
Point angle, degrees	135 ± 3	135 ± 3	135 ± 3	135 ± 3	135 ± 3	135 ± 3	135 ± 3
Web thickness (below split), inch	0.029 to 0.032	0.038 to 0.042	0.047 to 0.052	0.055 to 0.061	0.057 to 0.063	0.060 to 0.065	0.060 to 0.065
Chisel edge angle, degrees	115 to 125	115 to 125	115 to 125	115 to 125	115 to 125	115 to 120	115 to 120
Chisel thickness (after splitting), inch	0.004 to 0.008	0.004 to 0.008	0.004 to 0.008	0.004 to 0.008	0.004 to 0.008	0.004 to 0.008	0.004 to 0.008

All drills have point angles of 135 ±3 degrees and crankshaft (split) points, and are made from M33 high-speed steel.

TABLE 3-1.3.3-1. HIGH-SPEED STEEL USED FOR DRILLS IN DRILLING TITANIUM ALLOYS

AISI Grade of High-Speed Steel(a)	Commercially Pure	Titanium Alloy Ti-5Al-2.5Sn	Ti-8Al-1Mo-1V	Ti-6Al-4V	Ti-13V-11Cr-3Al
M1	S	S	S		G
M2					G
M3, Type 2	S	S	S		
M7	G,D	G,D	G,D		
M10	G,D,S	G,D,S	G,D,S	G,S	
M33	G,D	G,D	G,D		G
M34	G,D	G,D	G,D		
M36				S	
T4	G,D,S	G,D,S	G,D,S		
T5	G,D,S	G,D,S	G,D,S	G,S	

Note: G = general drilling; D = deep hole drilling; S = sheet drilling.

(a) See Table 3-0.1.3-2 for compositions.

throughout drilling. However, the high axial thrust required to keep the drill cutting, especially in heat-treated titanium alloys, can cause rapid operator fatigue. Furthermore, allowing the drill to advance rapidly on breakthrough, as is generally the case with hand feeding, will seriously shorten drill life by chipping the corners of the drill.[4,7]

The selection of feeds depends largely on the size of the drill being used. Generally, a feed range of 0.001 to 0.005 ipr is used for drills up to 1/4 inch in diameter. Drills 1/4 to 3/4 inch in diameter will use a heavier feed range, 0.002 to 0.007 ipr. Suggested feed rates for drills of diameters in the range of 1/16 to 1/2 inch diameter are given in Figure 3-1.3.4-1[4].

3-1.3.5 Drilling Speeds

Since the cutting zone is confined, drilling requires low cutting speeds for minimum cutting temperatures. The choice of speed used will depend largely on the strength level of the titanium material and the nature of the workpiece. Thus, speeds up to 80 fpm may be used for commercially pure titanium, while only 15 to 20 fpm should be used on aged Ti-13V-11Cr-3Al.[7]

Speeds should remain constant throughout the course of drilling. This means an "overpowered" drilling machine. Slow speed, high-torque drill motors should be used for portable power drills.

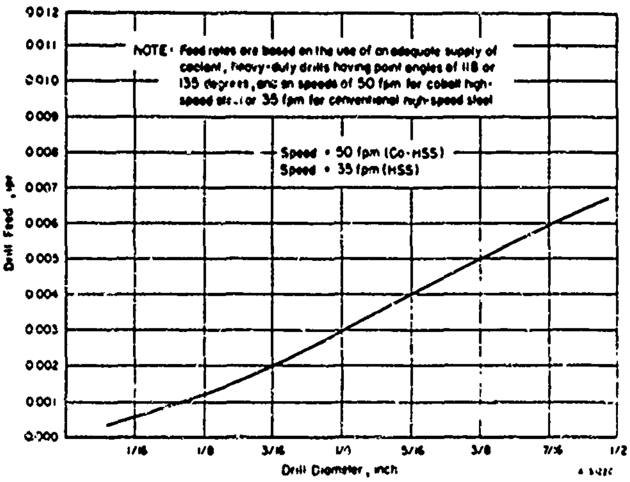


FIGURE 3-1.3.4-1. FEED RATE VERSUS DRILL DIAMETER FOR HIGH-SPEED DRILLS[4]

3-1.3.6 Cutting Fluids

Drilling titanium usually requires the use of cutting fluids. Although holes in single sheets with thicknesses up to twice the drill diameter can be drilled dry[6,11] sulfurized oils or sulfurized lanolin paste are recommended for low speeds and for drills less than 1/4 inch in diameter. A good coolant like soluble-oil-water emulsions can be used for the higher drilling speeds.[11,12]

A steady, full flow of fluid, externally applied at the cutting site, can be used, but the use of a spray mist seems to give better tool life. However, a two-diameter depth limit seems to exist for external applications. Hence, oil-feeding drills work best for deep holes.[8,11]

3-1.3.7 General Drilling Techniques and Inspection

Setup conditions for drilling titanium should provide overall setup rigidity and sufficient spindle power to maintain drill speeds during cutting. Successful drilling of titanium also depends on being able to reduce the temperature at the cutting lips.[35] This can be accomplished by:

(1) Using low cutting speeds
(2) Reducing the feed rate
(3) Supplying adequate cooling at the cutting site.

Thin sheet-metal parts must be properly supported at the point of thrust. This can be done with a backup block of AISI 1010 or 1020 steel. Where this is not possible because of part configuration, a low-melting alloy can be cast about the part.

When drilling stacked sheet, the sheets should be clamped securely with clamping plates to eliminate gaps between sheets.[4,7,35]

When starting a drilling operation, the drill should be up to speed and under positive feed as it advances toward the work. Never start with a dull drill; and use a triangular center-punch to mark the hole location on the part. Drill holes to size in one operation whenever possible. Center drills, or undersize starting drills, are usually not recommended. The use of drill bushings is desirable for close-tolerance holes.

The margin of the drill should be examined periodically for smearing in order to prevent oversizes holes. Also look for possible breakdowns that might occur at the outer corner of the lips. An arbitrary drill replacement schedule should be established to prevent work and drill spoilage.[11]

The nature of the chips produced indicates the condition of the drill during drilling. A sharp drill produces tight-curling chips without difficulty. As the drill progressively dulls, the cutting temperature rises and titanium begins to smear on the lips and margins. The appearance of feather-type chips in the flutes is a warning signal that the drill is dull and should be replaced. The appearance of irregular and discolored chips indicates that the drill has failed.[2,11,35] Out-of-round holes, tapered holes, or smeared holes are results of poor drilling action, with subsequent reaming problems, or even tap breakage when the holes are threaded.[7,11,12]

Chips should be removed at periodic intervals unless the cutting fluid successfully flushes away the chips.

When holes more than one diameter deep are being drilled, the drill should be retracted once for each half diameter of drill advance to clear the flutes.

Retraction should be done simultaneously with the stop of the feed to minimize dwell. The drill should be retracted quickly, but carefully, with the drill up to speed and under positive feed.[39,40]

When drilling "through holes", it is sometimes advisable not to drill all the way through on a continuous feed. Instead the drill should be retracted before breakthrough and the drill and hole flushed to remove the chips. Then the drill should be returned under positive feed and drilling through should be done carefully to avoid any "feed surge" at breakthrough.

All assembly drilling should be done with portable, fixed-feed, jig-mounted drilling machines. Hand drilling can be used, but the

practical limit appears to be the No. 40 drill. Above this diameter, insufficient feed is the result, with consequent heat buildup and short drill life. Hand drilling should not be used if the hole is to be tapped.[39]

Drilled holes will require reaming to meet the tolerances of Class I holes, unless a bushing is used immediately adjacent to the part. Drilled holes in sheet will probably require deburring on the exist side.

Operating data for drilling may be found in Table 3-1.3.7-1.

3-1.4 TAPPING OPERATIONS

3-1.4.0 Introduction

Tapping titanium is a difficult operation. The limited chip flow inherent in taps, and the severe galling action of titanium can result in poor threads, improper fits, excessive tap seizures, and broken taps. Titanium also tends to shrink on the tap at the completion of the cut.

Tapping difficulties can be minimized by reducing the thread requirements to 55 to 65 percent full thread,* and then tapping the fewest threads that the design will allow. Designers should also avoid specifying blind holes or through holes of excessive lengths. In both cases, the chips are confined and can cause rough threads and broken taps. Some relaxation in class-of-fit tolerances also should be considered.

The tapping operation itself requires sharp taps of modified conventional design, low tapping speeds, and an effective tapping lubricant.

3-1.4.1 Tapping Machines

A lead-screw tapping machine is recommended to ensure proper lead, a regulated torque, and a uniform hole size. Lead-screw tapping heads should be equipped with friction clutches. The clutch should prevent tap breakage when galling occurs because a very small amount of smear may result in immediate tap breakage.

Tapping machines should be rigid, accurate, and sensitive. Machine tapping, unless done on a sensitive machine, can result in excessive tap breakage and poor-quality work.

An electropneumatic oscillating-tapping machine, when properly set, cannot break a tap. Before any force is applied that might break a tap, the forward motion is interrupted and immediately reversed. The tap is driven by balanced spiral springs, and the tension is set just under the static breaking torque of the size of the tap being used. When the tap meets excessive resistance (which would ordinarily break the tap), the machine automatically reverses one-half revolution and then goes forward again.[4,47]

3-1.4.2 Setup Conditions

Requirements in tapping setups parallel those recommended for drilling. Machine tools that allow maximum rigidity, accuracy, and sensitivity should be used. Lead-screw tapping is recommended since less dependence is placed on the operator. The tapping head must be set for as short a stroke as possible. Hand tapping is not recommended because it lacks the required rigidity and is extremely slow and difficult.[7,11,12,47]

3-1.4.3 Taps and Tap Design

Gun taps have been used successfully.[14] Chip driving spiral point taps with interrupted threads and full eccentric relief also have been successful[3,48]. Taps should be precision ground and stress relieved. Two-fluted taps are usually used for 5/16-24 holes and smaller, while three-fluted taps are best for 3/8-16 holes and greater, and for other tapping situations. Taps with 2 flutes normally do not give the support the three-fluted taps provide.

Modifications of the conventional two-flute, spiral-point, plug-style H2-pitch-diameter taps can be used. The taps are modified by grinding away the threads behind the cutting edges down to the minor diameter, but leaving full-thread lands 0.015 inch wide backing up the cutting edges.[40] However, spiral-pointed tap cannot be expected to propel chips forward in holes that are more than two diameters long[7,48].

Taps should have tool angles suitable for titanium. This usually means:

(1) A spiral point angle large enough to allow chip flow out of the hole ahead of the tap.
(2) A relief angle large enough to prevent seizure but not so large as to cause jamming when backing out the tap. An eccentric pitch-diameter relief also can be used successfully.
(3) Sufficient cutting rake to provide a good shearing action.
(4) A chamfer of around 3 threads to provide a small depth of cut. A shorter chamfer results in high torque and possible tap breakage. A long chamfer produces long, stringy chips which may jam the tap during back-out operations. However, a plug chamfer gun tap can be used for shallow holes (holes less than one tap diameter deep).

*Some companies, however, have successfully tapped 75 percent threads.

TABLE 3-1.3.7-1. DRILLING TITANIUM ALLOYS WITH HIGH-SPEED-STEEL DRILLS[a]

Titanium Alloy	Alloy Condition[b]	Tool Material[c]	Cutting Speed, fpm
Commercially pure	Ann	M1, M2, M10	40 to 80
Ti-8Al-1Mo-1V	Ann	M1, M2, M10	20 (40 for sheet)
Ti-5Al-2.5Sn	Ann	M1, M2, M10	40
Ti-4Al-3Mo-1V	Ann	M1, M2, M10	40 (25 for sheet)
	STA	M33	20 for sheet
Ti-6Al-4V	Ann	M1, M2, M10	30 to 40
	STA	T15, M33	20 to 30
Ti-7Al-4Mo, Ti-6Al-6V-2Sn	Ann	M1, M2, M10	20
	STA	T15, M33	20
Ti-13V-11Cr-3Al	Ann	M1, M2, M10	20 to 30
	STA	T15, M33	15 to 20

Drill Diameter, inch	Feed[d], ipr: All But Ti-13V-11Cr-3Al	Feed[d], ipr: Ti-13V-11Cr-3Al
1/8	0.001-0.002	0.0005
1/4	0.002-0.005	0.001
1/2	0.003-0.006	0.0015
3/4	0.004-0.007	0.0015
1	0.004-0.008	0.002
2	0.005-0.013	0.003
3	0.005-0.015	0.004

Tool geometry	For general drilling operations, choose drill-geometry x, y, or z, depending on drill size; see Figure 3-1.3.2-1. For drilling sheet, use drill-geometry C, D, or B according to application; see Figure 3-1.3.2-2.
Cutting fluids used	Use a soluble oil-water emulsion or a sulfurized oil, the latter at lower speeds and for small drills (<1/4 inch). Chlorinated oils are also used provided oil residues are promptly removed by M.E.K. Holes in single sheets up to twice the drill diameter can be drilled dry.

(a) From References (2), (4), (6), (8), (11), (12), (14) (20)-(23), (35), (37)-(39), (42)-(46).
(b) Ann = annealed; STA = solution treated and aged.
(c) AISI designation.
(d) Use the lower feeds for the stronger or aged alloys. Data are for holes deeper than 1/2 inch. Somewhat higher feeds may be used for holes less than 1/2 inch deep. Medium and steady hand pressure is needed for hand drilling.

If rubbing is encountered in tapping it may be decreased by:

(1) Using interrupted threads with alternate teeth missing
(2) Grinding away the trailing edge of the tap
(3) Grinding axial grooves in the thread crests along the full length of the lands
(4) Employing either eccentric or con-eccentric thread relief.

Figure 3-1.4.3-1 illustrates the tap nomenclature referred to above.

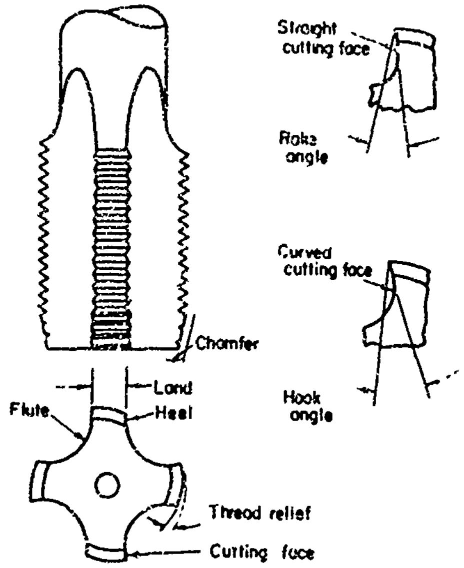


FIGURE 3-1.4.3-1. TAP NOMENCLATURE

Surface treatments contribute to successful tapping by reducing galling and increasing resistance to abrasion. Nitriding, oxide coating, or chromium plating have been employed successfully on taps used for titanium. Nitrided taps generally give the best performance.

3-1.4.4 Tap Materials

High-speed steel taps are used, AISI-M1 for tapping commercially pure titanium and AISI-M7 and M10 for titanium alloys. See Table 3-0.1.3-2 for compositions.

3-1.4.5 Size-of-Cut Requirements

The size of cut is determined by the chamfer given the tap. The chamfer that produces small chips without jamming the tap during the backing-out phase should be used.

3-1.4.6 Tapping Speed Requirements

It is important to limit the tapping speeds to those shown in Table 3-1.4.8-1, as cutting torque increases extremely rapidly beyond a certain threshold speed.

The high-strength titanium alloys require slower tapping speeds than the lower strength alloys, and much slower speeds than commercially pure titanium.

3-1.4.7 Cutting Fluids

The selection of cutting oils and compounds is extremely important because of the susceptibility of taps to seizure.

The paste-type cutting compounds (Lithopone or ZnS in oil) usually give the best tool life; however, they are generally not practical in production operations.[12]

Sulfurized oil, flood applied, is also satisfactory for tapping titanium. Molybdenum disulfide may be added to relieve persistent seizures. Barium hydroxide in water also can be used. Soluble oils, however, are not usually considered satisfactory.

Immediately before a hole is tapped the tap should be covered with a liberal amount of lithopone paste. If sulfurized oil is used, it should be forced on the tap throughout the tapping operation.[3,39]

Some fabricators recommend pretreating taps with colloidal molybdenum disulfide. The tap is dipped in a suspension of MoS_2 and white spirits, and then baked for 40 minutes at 200 C.[7,49]

3-1.4.8 General Tapping Techniques and Inspection

As a first requirement, holes for tapping should have been produced by sharp drills operating under positive-feed drilling conditions. Dull drills produce surface-hardened holes, which will magnify tapping difficulties. Sharp, clean taps must be used at low tapping speeds with recommended tapping compounds and under rigid tool-work setups. A stiff nylon brush pressed against the tap on the return stroke will help to remove chips and has been reported to increase tap life by at least 50 percent.

Where holes require complete threads close to the bottom of the hole, a series of two or three taps with successively shorter chamfers may be required.

Taps should be inspected carefully after use on six holes for possible smearing of lands. These smears may be hard to see but, if present, can cause premature tap breakage and oversized holes. The workpiece also should be inspected for possible torn threads and dimensional discrepancies. It should be remembered that most tapping is done on parts that are 80 to 90 percent finished;

hence, scrap from tapping operations can be very costly.[11]

Data for tapping titanium may be found in Table 3-1.4.8-1.

3-1.5 REAMING OPERATIONS

3-1.5.0 Introduction

Titanium and its alloys can be reamed successfully using proper precautions. Adhesion of titanium to the reamer must be prevented to avoid the production of oversized holes and poor finishes.

3-1.5.1. Selection of Machine Tools

Reaming can be done in a drill press, a screw machine, or a turret lathe; the choice depends on the reaming operation involved.

Drill press work is generally done in fixtures, and the reamer is guided in a bushing requiring a rigid holder. Screw machines and turret lathes may have a slight misalignment between the axes of the work spindle and the tool holder, necessitating the use of a floating holder.[52]

3-1.5.2 Reamers and Reamer Design

Titanium can be reamed with either a straight reamer or a spiral fluted reamer; however, the latter seems to produce better surface finishes. The conventional reamer has three basic tool angles; a chamfer angle, a rake angle, and a relief angle, as shown in Figure 3-1.5.2-1. The first two angles do not have any pronounced effect on reaming operations. The relief angle is most influential and should exceed 5 degrees to minimize smearing. On the other hand, relief angles in excess of 10 degrees cause vibration and chatter marks on the surface of reamed holes.[12]

Reamers with margins about 0.010 inch wide produce acceptable holes. Scoring is a problem with wider margins, and excessive chatter is likely to occur when margins are as narrow as 0.005 inch.[7-12]

3-1.5.3 Tool Materials

Both high-speed steel and carbide reamers can be used on titanium and its alloys. High-speed steel reamers, however, tend to deteriorate rapidly after tool wear starts. Carbide-tipped reamers are much better from the standpoint of tool life.[7,53]

3-1.5.4 Feeds

Light feeds are required to produce acceptable holes, meaning feeds between 0.002 and 0.016 ipr.[23,53] Sometimes, a heavy feed like 0.020 ipr is used, but feeds that heavy may lead to excessive pickup and scarred holes.[12]

Feeds should be increased in proportion to the size of the hole; it should be remembered, however, that larger amounts of metal removal can impair concentricity.[7,53]

3-1.5.5 Depth of Cut

The depth of cut, when varied between 0.002 and 0.016 inch (on the radius), shows no pronounced effect other than an increase in torque with increasing depths of cut.[7,12]

3-1.5.6 Cutting Speed

The recommended cutting speed for commercially pure titanium using high-speed reamers lies between 40 and 70 fpm, while titanium alloys require lower speeds such as 20 to 45 fpm. Carbide reamers may be used up to 250 fpm.[7,23,53]

3-1.5.7 Cutting Fluids

The most effective fluid for reaming titanium appears to be a sulfochlorinated mineral oil.[7,12]

3-1.5.8 Reaming Techniques

There seems to be no single set of reaming conditions that will give optimum results by all criteria. Nevertheless, the basic precautions for machining titanium should be heeded. These

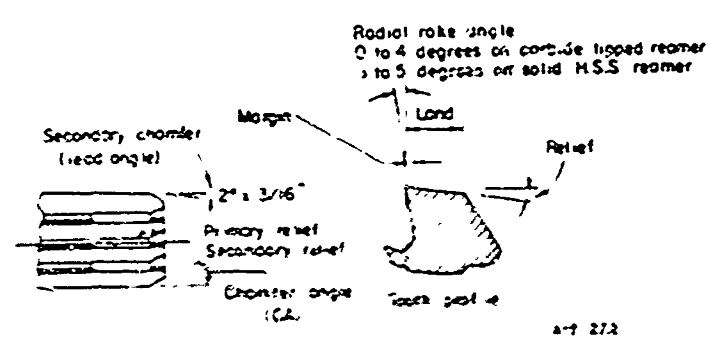


FIGURE 3-1.5.2-1. NOMENCLATURE FOR FLUTED REAMERS

TABLE 3-1.4.8-1. TAPPING DATA FOR TITANIUM AND ITS ALLOYS USING HIGH-SPEED STEEL TAPS[a]

AISI Type High-Speed Steel[b]	M1, M7, M10 (nitrided)	
Tap Styles		
Tap Size	5/16-24 and smaller	3/8-16 and greater
Number of Flutes[c]	2 or 3	3 or 4
Tap Geometry		
Spiral Point Angle, degrees	10 to 17	
Spiral Angle, degrees	110	
Relief Angle, degrees	2 to 4	
Cutting-Rake Angle, degrees	6 to 10	
Chamfer Angle, degrees	8 to 10 or 3 to 4 threads	
Tapping Speeds, fpm		
Unalloyed titanium	30-50	
Ti-5Al-2.5Sn	10-25	
Ti-4Al-3Mo-1V	10-25	
Ti-4Al-3Mo-1V, aged	10	
Ti-6Al-4V, annealed	10-20	
Ti-6Al-4V, aged	10-15	
Ti-8Al-1Mo-1V, annealed	10-15	
Ti-7Al-4Mo; Ti-6Al-6V-2Sn, annealed	15	
Ti-7Al-4Mo; Ti-6Al-6V-2Sn, STA	10-20	
Ti-13V-11Cr-3Mo, annealed	8-15	
Ti-13V-11Cr-3Mo, aged	5-9	
Tapping Lubricants	Lithopone paste 30% SAE 20 oil, 70% lithopone); heavy sulfurized oil, sometimes fortified with molybdenum disulfide; barium hydroxide in water (5% by weight); highly chlorinated or sulfochlorinated oils followed by a thorough degreasing with MEK.	

(a) From References (3),(14),(19)-(23), (39),(40),(44),(47)-(51).

(b) M1 high-speed steel is adequate for unalloyed titanium. M10 high-speed steel is best for titanium alloys. Nitrided taps generally give the best performance.

(c) Taps with two flutes normally do not give the support that the three or four-fluted taps provide; hence, the latter two types should be used for the larger sizes.

include adequate rigidity of setup, sharp tools, and a positive feed to prevent riding without cutting. Chatter, if present, can be eliminated by altering tool design, size of cut, and cutting speed.

Undersized holes (0.01 to 0.020 undersize) should be drilled or bored prior to the reaming operation. (6,7)

Cutting speeds and feeds, along with the tool geometry concerned, are shown for general reaming in Table 3-1.5.8-1.

3-1.6 BROACHING OPERATIONS

3-1.6.0 Introduction

Titanium can be broached under the general setup conditions required by the other machining operations. Because of the interrupted nature of the cut, welding of the chip to the cutting edge is quite troublesome as in milling. This tendency increases as the wearland develops. As the wearland increases, so does the tendency for titanium to smear on the cutter. The result is poor finish, rapid wear, and loss of tolerances. (23)

Titanium, nevertheless, can be broached successfully. In fact, a surface finish of 6 to 28 microinches, rms, can be expected for the tool designs and speeds shown herein. (7,12)

3-1.6.1 Machine Tools for Broaching

There are about six styles or types of machine tools available for broaching; they may be either manually or power operated. They include horizontal broaching machines, vertical surface broaching machines, single or dual ram, vertical pull-up (also pull-down) broaching machines, and broaching presses. The latter type can exist as foot presses, arbor presses, rack presses, friction tion presses, and power presses. (55-57)

The type of broach required is the most important factor in determining the type and size of broaching machine to be used. In general, the broach determines and controls the machine type, stroke, and capacity and not vice versa. Other variables include type of broaching operation (i.e., internal broaching, external broaching, etc.), production rate, total production, and number of operations to be given on a single machine. (55-57)

3-1.6.2 Broaches and Broach Design

Tool design is a very important factor that affects broaching performance. The relief angle, rake angle, and the rise per tooth seem to be the more important elements. Teeth should have a positive rake so that the chips will curl freely into the gullets. The gullet size should be large enough to accommodate the chips formed during the cutting action. (7,12)

Figure 3-1.6.2-1 illustrates some of the elements of broach geometry.

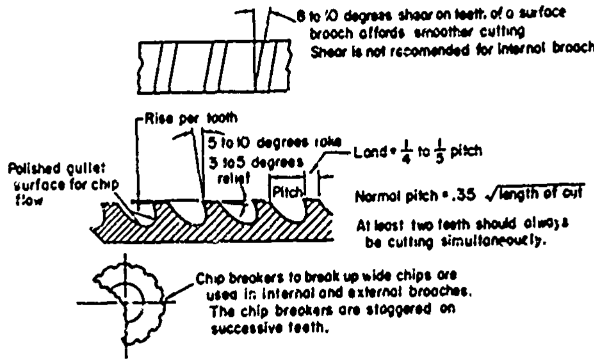


FIGURE 3-1.6.2-1. NOMENCLATURE FOR BROACHES

Titanium usually requires relief angles somewhat higher than the 1/2 to 2 degrees normally used in broaching other materials. If the relief angle is too small, metal pickup on the land relief surface can seriously affect the quality of the broached surface. Accordingly, relief angles between 3 and 5 degrees have been adopted and used successfully. (7,12)

A rake or hook angle of 20 degrees is normally recommended for broaching conventional materials. For titanium, however, a reduction to +5 degrees will improve broaching performance to a marked degree. The smaller rake angle provides greater support for the cutting edge, and improves heat transfer from the cutting zone. The maximum rake is about +10 degrees. An increase beyond this value invites tool failure.

TABLE 3-1.5.8-1. REAMING DATA FOR TITANIUM ALLOYS[a]

Titanium Alloy	Alloy Condition[b]	Tool Material[c] High-Speed Steel	Tool Material[c] Carbide	Cutting Speed, fpm High-Speed Steel Initial	Cutting Speed, fpm High-Speed Steel Final	Cutting Speed, fpm Carbide Tipped Initial	Cutting Speed, fpm Carbide Tipped Final	Reamer Diameter, inch	Feed, ipr, for Reamer Shown[d] Commercially Pure, Ann.	Feed Ti-13V-11Cr-3Al Ann.	Feed Ti-13V-11Cr-3Al STA	Feed All Other Titanium Alloys[d]
Commercially pure	Ann.	M2	C-2	40	70 to 100	65	250 to 375	1/8	0.003	0.002	0.002	0.002
Ti-8Al-1Mo-1V	Ann.	M2	C-2	20	30	50	120	1/4	0.005	0.005	0.004	0.005
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	Ann.	M2	C-2	20	45	50	175	1/2	0.008	0.007	0.006	0.007
Ti-4Al-3Mo-1V	Ann. STA	M2	C-2 C-2	20 --	45 25	50 --	175 100	1	0.011	0.009	0.008	0.009
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	Ann. STA	M2 M2	C-2 C-2	20 15-20	35 30	50 35	150 120	1-1/2	0.014	0.012	0.010	0.012
Ti-7Al-4Mo Ti-6Al-6V-2Sn	Ann. STA	M2 M2	C-2 C-2	20 18-20	30 25	35 35	120 100	2	0.016	0.015	0.012	0.015
Ti-13V-11Cr-3Al	Ann. STA	M2 M2	C-2 C-2	20 10-20	30 25	50 35	150 100					

Tool Angles, degrees

		Helix	Radial Rake	Relief	Clearance	Chamfer	Lead	Margin, inch
Tool Geometry	High-speed steel	10	3 to 5	5 to 10	10 to 15	45	--	0.010-0.015
	Carbide	7	6	5 to 10	10 to 15	45	2' x 3/16"	0.010-0.015

(a) From References (6), (12), (20)-(23), (53), (54).
(b) Ann. = annealed; STA = solution treated and aged. The softer unalloyed titanium may be reamed at the higher speed shown.
(c) AISI designations for steels; CISC designations for carbides.
(d) Feeds are the same for both annealed and heat-treated alloys.

The normal recommendation for the rise per tooth in broaching steel is 0.0005 to 0.003 inch. Titanium materials, however, should be broached at 0.001 to 0.006 inch per tooth, depending on the alloy and its condition and the broaching operation. The lower values of this range should provide lower cutting forces and better surface finishes.(7,12)

Broaches that have been wet ground may improve tool performance. Careful vapor blasting also may help tool life and finishes by reducing the tendency for smearing.(23)

Solid broaches are sometimes made slightly oversize (0.0005 inch) to compensate for the slight springback that will occur when the cut is completed.

3-1.6.3 Tool Materials

Any type of high-speed steel should work reasonably well as a broaching-tool material for titanium. The standard AISI Types T1, M2, and M10 should give good performance in the speed ranges recommended herein.(7,12) Their compositions are shown in Table 3-0.1.3-2.

3-1.6.4 Depth of Cut

The depth of cut is governed by the "rise per tooth" of the broach. A "rise per tooth" in the range of 0.002 to 0.005 has been used successfully when a +5-degree relief is employed. If a 3-degree relief is used, the rise should be reduced to 0.001 ipt.(7)

3-1.6.5 Cutting Speed

Some titanium alloys have shown a marked sensitivity to changes in cutting speed. Consequently, it appears reasonable to recommend low speeds for this type of operation. This means that cutting speeds should be restricted to the range of 20 to 30 fpm. When broaching dovetails, the speed should be reduced to 10 to 12 fpm.(7,12)

3-1.6.6 Cutting Fluids

Sulfurized mineral oil, oil-in-water emulsions, and carbon dioxide sprays have been used during the broaching of titanium. Sulfurized oils seem to give the best results because they minimize friction, improve surface finish, and reduce wear rates. A prior application of an oil with a high-strength film to the surface to be broached will greatly minimize the chip-welding tendency and prolong tool life between grinds.(7,12)

3-1.6.7 Broaching Techniques

Rigidity of work and tool is necessary to avoid a consecutive series of "flat surfaces" on the workpiece. Surface broaching requires much greater rigidity in fixturing than does hole broaching. Hole broaching apparently provides an inherent rigidity derived from the cutter motion against the work-holding device or fixture.(7,12)

The broach should not ride on the work without cutting, and chips should be removed from broaching tools before each succeeding pass. Any excessive wearland development or undue smearing should be noted at that time. Tools should be kept sharp to reduce the tendency of smearing (of the land), which eventually leads to tool failure.(7)

Operating data for broaching titanium and its alloys are listed in Table 3-1.6.7-1.

3-1.7 BAND SAWING

3-1.7.0 Introduction

Difficulties in band sawing titanium and its alloys can be minimized by selecting a saw band with the proper saw pitch suited to the work thickness involved. The combination of band velocity and feed also influences the economic tool life.

The roughness on the cut surface usually ranges from 60 to 200 microinches, rms. Finishes better than 125 microinches rms are obtained by using higher speeds, lighter feeds, and a fine saw pitch.(7,58)

3-1.7.1 Machine-Tool Requirements

Rigid, high-quality band-saw equipment powered with motors of at least 2 horsepower should be used. The machines should possess automatic positive feeding and band-tensioning features. In addition, they should have a positive-flow, recirculating-type coolant system, and should be vibration-free.(7,12,58)

Hand or gravity-type feeds do not produce satisfactory results when sawing titanium.

3-1.7.2 Saw Bands and Saw Band Design

Precision and claw-tooth saw bands are used for cutting titanium. The widest and thickest band that can produce the smallest radius desired on the part should be selected. The following band widths will cut the minimum radii indicated:(59)

Saw Width, inch	Minimum Radii Cut, inch
1/16	Square
3/32	1/16
1/8	1/8
3/16	5/16
1/4	5/8

TABLE 3-1.6.7-1. BROACHING DATA FOR TITANIUM AND ITS ALLOYS[a]

Titanium Alloy	Alloy Condition[b]	Type High-Speed Steel[c]	Roughing: Cutting Speed, fpm	Roughing: Depth of Cut, inch	Finishing: Cutting Speed, fpm	Finishing: Depth of Cut, inch
Commercially pure	Ann.	T5	20-35	0.004-0.007	30-55	0.002-0.004
Ti-8Al-1Mo-1V	Ann.	T5	10	0.003-0.006	16	0.0015-0.003
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	Ann.	T5	15	0.003-0.006	22	0.0015-0.003
Ti-4Al-3Mo-1V	Ann.	T5	15	0.003-0.006	22	0.0015-0.003
	STA	T15	7	0.002-0.004	10	0.001-0.002
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	Ann.	T5	12	0.003-0.006	18	0.0015-0.003
	STA	T15	8	0.002-0.005	12	0.001-0.002
Ti-7Al-4Mo Ti-6Al-6V-2Sn	Ann.	T5	10	0.003-0.006	16	0.0015-0.003
	STA	T15	7	0.002-0.004	10	0.001-0.002
Ti-13V-11Cr-3Al	Ann.	T5	11	0.003-0.006	17	0.0015-0.003
	STA	T15	6	0.002-0.004	9	0.001-0.002

Tool Geometry		Rake Angle (Hook), degrees	Relief Angle, degrees	Rise per Tooth, inch
Tool Geometry	Roughening	+5 to +10	3 to 4	Same as cut depth
	Finishing	+5 to +10	2 to 3	Ditto

(a) From Refs. (7, 12, 23).
(b) Ann. = annealed; STA = solution treated and aged.
(c) AISI designations used.

Saw Width, inch con't	Minimum Radii Cut, inch con't
3/8	1-7/16
1/2	2-1/2
5/8	3-3/4
3/4	5-7/16
1.0	7-1/4

Wider saw bands provide greater stability when the saw is pretensioned.

Figure 3-1.7.2-1 illustrates some of the common terms used in describing sawing operations.

Two important design features of a saw band are the "pitch" or the number of teeth per inch and the "set" of the teeth. The selection of saw pitch for a saw band cutting titanium depends mainly on the cutting-contact area. If the pitch is too coarse, the feeding force on each tooth will be excessive. On the other hand, if the pitch is too fine, the chips will crowd or fill the gullets. In general, the coarsest pitch consistent with desired finish should be selected; however, at least two teeth should always contact the cut.

The saw set creates clearance to prevent the trailing surface of the band from binding. It determines the kerf and hence the amount of metal removed. A fine-pitch saw band with a light set usually gives the best finish, particularly when used with higher band velocities and low feed rates. This combination also produces a slot (or kerf) which approaches the overall saw set dimension.[58]

The following tabulation gives some data for raker set, precision-type band saws used for power band sawing titanium.[59]

Pitch Teeth per Inch	Width, inch	Gage inch	Nominal Set, inch
4	1	0.035	0.060
6	1	0.035	0.045; 0.058
8	1	0.035	0.045; 0.058
10	1	0.035	0.045; 0.058

A right-left raker set combined with the coarsest pitch consistent with the work thickness and the desired finish is usually adequate for most applications. For some of the stronger alloys of titanium, better results can be expected from the modified design shown in Figure 3-1.7.2-2. First, the extreme tips of the teeth are ground flat, and then a 4 to 6-degree clearance angle is added to the stubs. Next, a 90-degree face-cutting angle is ground on each tooth. A band of this design can be reground three or four times, provided it is removed from production before failure occurs.[7,58]

3-1.7.3 Tool Materials

Saw bands utilizing high-speed steel are recommended for sawing titanium. An appropriate heat treatment produces a microstructure that remains strong at elevated temperatures in a reasonably flexible band.[7,58]

3-1.7.4 Feeds

Feeds in the range of 0.00002 to 0.00012 inch per tooth can be used successfully. The smaller feeds give the best tool life, but the heavier feeds increase productivity and may be more economical. Excessive feeds, however, clog the teeth with chips before they emerge from the kerf and reduce cutting rates.

Feeding forces must be reduced as the saw pitch decreases, to prevent overloading individual of teeth. On the other hand, feeding pressures so light that the teeth do not penetrate the work cause excessive abrasion and rapid dulling.[7,12,58]

3-1.7.5 Cutting Rate

The maximum cutting rate in band sawing is affected mainly by the thickness of the workpiece. Faster cutting rates are achieved in sawing solid bars 1 inch or greater in thickness (or diameter) since more teeth can be loaded uniformly at the same time. For thinner sections, the limited number of engaged teeth requires a reduction in cutting rate to reduce the feed per tooth. Cutting rates ordinarily should not exceed 1 in.^{2}/min. Higher rates may cause inaccurate cutting and can damage the saw set. In general, cutting rates are smaller for band sawing tubing and structural mill shapes than bars and plates.[7,58]

3-1.7.6 Cutting Speed

Band velocity is a critical variable in sawing titanium. Excessive cutting speeds cause high cutting temperatures and unwanted vibrations.[58] Band velocities used for sawing titanium and its alloys usually range from 50 to 120 fpm, depending on the alloy, surface finish, cutting rate, and tool life desired.[7,12,58] The following tabulation subdivides this range according to alloy:

Titanium Material	Cutting Speeds, fpm
Commercially pure	85 to 100
Ti-5Al-2.5Sn	60 to 70
Ti-6Al-4V	35 to 45

3-1.7.7 Cutting Fluids

Cutting fluids used in band sawing of titanium include soluble oils, sulfurized oils, and

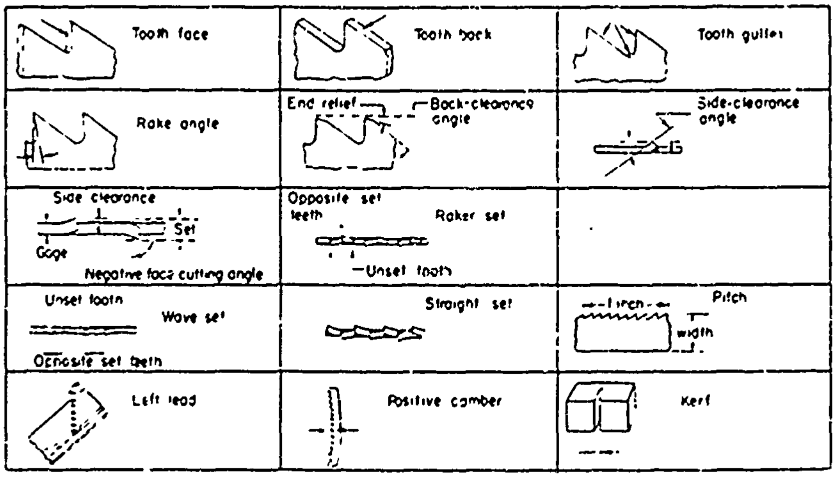


FIGURE 3-1.7.2-1. ILLUSTRATIONS OF SOME COMMON TERMS USED IN ALLOYS(58-59)

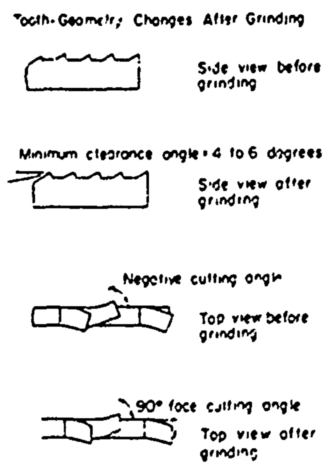


FIGURE 3-1.7.2-2. A MODIFIED DESIGN SUGGESTED FOR SAWING HARD TITANIUM ALLOYS(58)

chlorinated oils.(7,12,58-60) Fluids flowing force fully from shroud-like nozzles will penetrate the kerf and prevent chips from adhering to the tooth faces and gullets. An atomized spray of soluble oil under 40 psi of psi of air pressure also has been used with good results.(58) Boston suggests that the latter technique might be preferable if the rubber tires on the band-saw wheels are subject to reaction with oil-base fluids.

3-1.7.8 Band Sawing Techniques

Maximum rigidity is needed when sawing titanium and is favored by using the widest and thickest band permitted by the band wheel and the radii to be cut. The band should be pretensioned to approximately 12,000 psi to minimize unnecessary bending of the saw band in the cut.(12,58)

Guide inserts should be adjusted to a snug fit to ensure accurate cuts and minimum "lead". For the same reasons, the band support arms should be close to the work.

Heavy oxide films will cause problems in band sawing of titanium. In fact, an oxide coating as thin as 0.001 inch will reduce the life of new saws drastically. This trouble can be solved by breaking this surface at the line of cut with a used saw blade.

During the sawing operations, the saw band must not skew in the cut. If the cutting time starts to increase rapidly, the saw band should be replaced.(7,58)

Operating conditions for band sawing titanium sheet, plate, bars, and tubing are suggested in Tables 3-1.7.8-1 to 3-1.7.8-5 inclusive.

TABLE 3-1.7.8-1. RECOMMENDED[a] SPEEDS, FEEDS, AND CUTTING RATES FOR BAND SAWING TITANIUM AND ITS ALLOYS(5,58)

Line	Titanium Material	Brinell Hardness Number	Band Speed, fpm	Unit Feed, inch/tooth	Cutting Rate in.^{2}/min
1	Commercially pure	190-240	50-90	0.00002 to 0.00012	0.25 to 0.75
2	Titanium alloys	205-340	50-100[b]	0.00002 to 0.00012	0.50 to 1.0

(a) Based on 5-inch rounds and a 6-pitch saw.
(b) Use lower speeds for the stronger alloys, i.e., between 50 and 70 fpm.

TABLE 3-1.7.8-2. PITCHES OF BAND SAWS RECOMMENDED FOR SAWING DIFFERENT WORK THICKNESSES(7,58)

Line	Work Thickness, inch	A/L Ratio(a), inch	Appropriate Pitch, teeth per inch
1	7/64 to 5/32	0.10 to 0.15	18
2	5/32 to 3/16	0.15 to 0.28	14
3	3/16 to 3/8	0.28 to 0.375	10
4	3/8 to 1.0	0.375 to 1.0	6
5	1.0 and greater	1.0 and greater	6

(a) A/L represents the ratio "area of cut" to the "length of the cut". In circular sections, A/L equals $1/4\pi$ of the diameter. In square or rectangular sections, it equals the cut thickness.

TABLE 3-1.7.8-3. RECOMMENDED MODIFICATIONS OF CUTTING RATES FOR PIPE, TUBING, AND STRUCTURAL SHAPES(7,58)

Line	Minimum Wall Thickness to be Sawed, inch	Fraction of Minimum Cutting Rates
1	Up to 3/16	0.40
2	3/16 to 3/8	0.50
3	3/8 to 5/8	0.60
4	5/8 to 1.0	0.70
5	1.0 inch and over	1.00

TABLE 3-1.7.8-4. LINEAR FEEDS WHEN BAND SAWING TITANIUM SHEET OR WIRE(7,58)

	Linear Feeds, in./min, for the Band Velocities Indicated							
Unit Feed, inch/tooth	50 fpm	60 fpm	70 fpm	80 fpm	90 fpm	100 fpm	110 fpm	120 fpm
		Saw Pitch			18 teeth/in.			
		Sheet						
		Thickness			7/64-5/32 in.			
		A/L Ratio			0.10-0.15			
		Wire, A/L Ratio			0.10-0.15			
0.00002	0.22	0.26	0.30	0.35	0.39	0.43	0.47	0.52
0.00003	0.32	0.39	0.45	0.52	0.58	0.65	0.71	0.78
0.00004	0.43	0.52	0.60	0.69	0.78	0.86	0.95	1.04
0.00006	0.65	0.78	0.91	1.04	1.17	1.30	1.43	1.55
0.00008	0.86	1.04	1.21	1.38	1.55	1.73	1.90	2.07
0.00010	1.08	1.30	1.51	1.73	1.94	2.16	2.38	2.59
0.00012	1.3	1.55	1.81	2.08	2.33	2.59	2.85	3.11
		Saw Pitch			14 teeth/in.			
		Sheet						
		Thickness			5/32-2/16 in.			
		A/L Ratio			0.10-0.28			
		Wire, A/L Ratio			0.10-0.15			
0.00002	0.17	0.20	0.24	0.27	0.30	0.34	0.37	0.40
0.00003	0.25	0.30	0.35	0.40	0.45	0.50	0.56	0.61
0.00004	0.34	0.40	0.47	0.54	0.60	0.67	0.74	0.81
0.00006	0.50	0.61	0.71	0.81	0.91	1.01	1.11	1.31
0.00008	0.67	0.81	0.94	1.08	1.21	1.34	1.48	1.62
0.00010	0.84	1.01	1.18	1.35	1.51	1.68	1.85	2.02
0.00012	1.01	1.21	1.41	1.61	1.81	2.02	2.22	2.42

TABLE 3-1.7.8-5. LINEAR FEEDS WHEN BAND SAWING TITANIUM BARS, PLATE, AND ROUNDS[7,58]

Unit Feed, inch/tooth	Linear Feeds, in./min, for the Band Velocities Indicated: 50 fpm	60 fpm	70 fpm	80 fpm	90 fpm	100 fpm	110 fpm	120 fpm
Saw Pitch: 10 teeth/in.; Bar and Plate Thickness: 3/16-3/8 in.; A/L Ratio: 0.28-0.375; Rounds, A/L Ratio: 0.28-0.375								
0.00002	0.12	0.14	0.17	0.19	0.22	0.24	0.26	0.29
0.00003	0.18	0.22	0.25	0.29	0.32	0.36	0.40	0.43
0.00004	0.24	0.29	0.34	0.38	0.43	0.48	0.53	0.58
0.00006	0.36	0.43	0.50	0.58	0.64	0.72	0.79	0.86
0.00008	0.48	0.58	0.67	0.77	0.86	0.96	1.06	1.15
0.00010	0.60	0.72	0.84	0.96	1.08	1.20	1.32	1.44
0.00012	0.72	0.86	1.01	1.15	1.30	1.44	1.58	1.73
Saw Pitch: 6 teeth/in.; Bar and Plate Thickness: 3/8 in. and greater; A/L Ratio: 0.375 and greater; Rounds, A/L Ratio: 0.375 and greater								
0.00002	0.07	0.09	0.10	0.12	0.13	0.14	0.16	0.17
0.00003	0.11	0.13	0.15	0.17	0.20	0.22	0.24	0.26
0.00004	0.14	0.17	0.20	0.23	0.26	0.29	0.32	0.35
0.00006	0.22	0.26	0.30	0.35	0.39	0.43	0.48	0.52
0.00008	0.29	0.35	0.40	0.46	0.52	0.58	0.63	0.69
0.00010	0.36	0.43	0.50	0.58	0.65	0.72	0.79	0.86
0.00012	0.43	0.52	0.60	0.69	0.78	0.86	0.45	1.04

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3-2 Grinding and Abrasive Cutting

3-2.1 PRECISION WHEEL GRINDING

3-2.1.0 Introduction

Titanium and its alloys can be ground at about the same rate as hardened high-speed steels and die steels. Moderately light cuts are recommended, and periodic dressings are required to keep the wheel in proper condition.

Titanium can crack when ground under the conditions normally used for production steels. Under proper grinding conditions for titanium, however, grinding cracks are no longer the problem they once were when alloys were not of the present high quality. An etching solution containing hydrofluoric and nitric acids, sometimes used to reveal cracking, may, by itself cause cracks if the nitric acid content is too low and high tensile stresses exist in surface layers.

Smearing of ground titanium surfaces primarily results from wheel loading, although setup rigidity, wheel speed, and wheel characteristics all contribute to this problem.

Grinding difficulties can be minimized by employing the proper type of wheels at low wheel speeds and feeds, and by flooding the grinding area with inhibitor or purging types of cutting fluids. Grinding temperatures must be kept low to keep stresses low.

In spite of the advances made in the last few years, the aircraft and missile industries still retain a cautious attitude toward grinding of titanium.[1]

If a choice of finish-machining methods exists, serious considerations should be given to turning, boring, or milling operations rather than grinding. These operations require less time than grinding and give excellent surface finishes.[1]

3-2.1.1 Equipment

Many high-quality grinders are available today. Most of the existing machines can be set for the required light downfeeds, although some have no means of adjusting the spindle speed. Furthermore, not many production grinders are equipped with automatic wheel-wear compensation. These devices improve dimensional control, especially when softer wheels are used. Several existing grinders are being modernized to provide wheel speeds suitable for titanium and other high-strength alloys. Devices for automatic gaging and sizing, wheel dressing, and wheel compensation are being added to the ultra-precision grinders. Increased rigidity in the spindle system, together with automatic wheel balancing are highly recommended features for grinding the high-strength thermal-resistant materials.[1,2]

3-2.1.2 Wheel Properties and Characteristics

Wheel wear occurs by attrition, which causes flat spots on individual grains; by grain fractures, which expose new and sharp cutting points and edges; and by bond fracture, which causes abrasive grains to leave the wheel individually or in clusters.[3]

Normal attrition of a grinding wheel involves, as a continuous process, a gradual smoothening of the individual abrasive grains during cutting. This is followed by intergranular fractures, which are supposed to provide successively new, sharp-edged cutting surfaces until the workpiece material is deposited on and/or between the abrasive grains, a situation that can cause either loading or glazing. If the grains break away too rapidly, either during grinding or by frequent wheel dressing, wheel wear becomes excessive.[2]

Loading can occur whether the wheel is sharp or dull, although dulling will intensify the loading process. As loading progresses, the grinding action decreases until burnishing occurs. Then the grinding temperature rises, causing high residual tensile stresses in the ground surface, and low-grinding ratios. Glazing is similar, except that the tips of the grain wear smooth and become shiny through friction. Smooth wheels resulting from either cause burnish the workpiece and may result in burning, high residual stresses, and cracked surfaces.[3]

The problems described above can be controlled by choosing the right grinding wheel.

Grinding wheels are available in various combinations of grit sizes, wheel hardenesses, and bond materials. These attributes influence metal-removal rates and wear for specific grinding conditions.

The size of the abrasive grains influences the efficiency of grinding by affecting the rate of intergranular fracturing, and the consequent supply of fresh cutting edges. Smaller grains tend to leave the wheel prematurely, resulting in faster wear. Larger grains are usually more difficult to penetrate and fracture. Consequently, they dull excessively before leaving the wheel. The optimum grit size for aluminum oxide wheels is between 60 and 80. The optimum grit size for silicon carbide wheels is between 80 and 100.[3-6]

The material used to bond the abrasive grits determines the wheel hardness. It is usually desirable to use the hardest wheel that will not cause burning or smearing of hard alloys, or produce chatter on softer alloys.

For this reason, the medium grades, J to M, seem to be the most suitable for titanium. For example, the "M" grade in aluminum oxide wheels exhibits between 30 to 50 percent higher grinding ratios than the softer "K" grade, depending on the cutting fluid used. The softer wheels, however, perform better at higher speeds; the harder wheels at somewhat slower speeds.[4,5]

Vitrified bond materials seem to give the best performance, possibly because they are more porous. As such, they permit better swarf clearances and result in lower grinding temperatures.[2,3,6]

3-2.1.3 Abrasive Materials Used

The choice of a silicon carbon or aluminum oxide wheel depends on the grinding application.

Silicon carbide wheels usually produce a better surface finish. On the other hand, aluminum oxide wheel may give lower residual stresses in the workpiece because they are used at lower speeds. Silicon carbide wheels, unfortunately, need grinding oils, and this, plus the higher grinding speeds involved, produce a definite fire hazard.

Wheels made with black or regular silicon carbide abrasive, such as 37C*, seem to be inferior to those with aluminum oxide abrasives made by the same manufacturer from the standpoint of wheel wear when each is run at its optimum speed with the same grinding fluid. The optimum speed for silicon carbide wheels is much higher than that of an aluminum oxide wheel. In fact, if a wheel must be operated in the vicinity of 6000 fpm, because of equipment limitations, silicon carbide wheels give better results than aluminum oxide wheels.[2,3,5]

Aluminum oxide wheels with special friable abrasives, such as 32A* or its equivalent, have been found to be the most satisfactory for titanium. However, white aluminum oxides, such as Grade 38A*, can be substituted at a sacrifice of about 20 percent in wear rate.[6]

Table 3-2.1.3-1 shows some abrasive-grain classifications, listed by manufacturers, which may be comparable. However, grinding wheels from different suppliers are not necessarily identical.

Table 3-2.1.3-2 explains the nomenclature used for grinding wheels and illustrates a typical marking sequence.

* Norton Symbol.

3-2.1.4 Feeds

Two types of feeds are involved in grinding: the downfeed and the cross feed. The former is similar to the depth of cut in machining, while the latter corresponds to the feed.

The lightest downfeeds (0.0005 ipp) seem to give the highest G-ratios over a wide range of cross feeds (between 0.025 and 0.25 ipp). However, as the downfeed is successively increased from 0.0005 to 0.0015 ipp, the grinding ratio falls, and does so more rapidly as the unit cross feed is increased. Hence, a cross feed of around 0.050 ipp is normally used, together with downfeeds of between 0.0005 and 0.001 ipp. Heavier downfeeds can cause burning and excessive wheel wear. The cross feed, however, may be increased to 0.10 ipp, provided the downfeed is decreased to 0.0005 ipp.[2,3,5,6]

3-2.1.5 Grinding Speed

Using a given grinding wheel and coolant, an optimum grinding-speed range can effect much higher grinding ratios (G-ratios) than a speed a few hundred feet per minute faster or slower. For the aluminum oxide wheel 32A60VBE, these optimum speeds appear to be between 1500 and 2800 fpm for both grinding oils and rust-inhibitor coolants.[3,5,6] For silicon carbide wheels, the optimum speed seems to be in the range from 4000 to 4500 fpm when a grinding oil is being used.[5] Where it is necessary to use the conventional speed of about 6000 fpm, silicon carbide wheels give the best wheel life, but surface damage can be significant.

Wheel speeds of 4000 fpm can be used with silicon carbide wheels and sulfochlorinated oils to produce a good combination of surface finish and dimensional tolerance with relatively low residual stresses. Lower residual stresses are produced at low wheel speeds (1800 fpm) using aluminum oxide grinding wheels and rust-inhibitor-type fluids.[7]

A word should be added about table speed. The G-ratio for the 32A60VBE wheel running at 1600 fpm peaks at 200 ipm table speed. This speed, however, is too low for practical grinding. Hence, the recommended table speeds are in the somewhat higher range of 300 to 500 ipm.[2,5,6]

3-2.1.6 Grinding Fluids

The selection of a grinding fluid is very important, since the application involves not only cooling but also inhibiting the surface action between titanium and the abrasive wheel. Titanium and its alloys should never be ground dry. Dry grinding results in excessive residual stresses in the ground part in addition to the fire hazard that is present from dry titanium-metal dust.[5]

TABLE 3-2.1.3-1. TYPES OF ALUMINUM OXIDE AND SILICON CARBIDE ABRASIVES USED FOR GRINDING TITANIUM

Abrasive Manufacturer	Abrasive Designation: Special Friable Aluminum Oxide	White Aluminum Oxide	Black or Regular Silicon Carbide
Norton	32A	38A	37C
Cincinnati	4A	9A	6C
Carborundum	--	AA	C
Bay State	3A-8A	9A	2C
Chicago	52A	53A	49C
Desanno	7A	9A	C
Macklin	26A	48A	C
Simonds	7A	8A	C
Sterling	HA	WA	C

Water alone is not suitable, and ordinary soluble oils do not produce good grinding ratios, although they do reduce the fire hazard of grinding. (See Table 3-2.1.7-1, for suitable grinding fluids.)

The highly chlorinated oils* give some of the highest G-ratios, especially with silicon carbide wheels. Some of the conventional sulfurized and chlorinated grinding oils also have proved quite satisfactory. Some of the nitrite-amine type rust inhibitors give good results, especially with aluminum oxide wheels.[5,8]

The degree of concentration or dilution of a grinding fluid plays an important part in the grinding action. Maximum G-ratios are obtained with undiluted oils. When grinding oils are diluted with plain mineral oil, most of their advantages are lost.

The rust inhibitors should be used at about 10 percent concentration. This gives a reasonable grinding ratio without the practical difficulties caused by higher concentrations.

All fluids should be filtered to remove grit and to prevent "fish tail" marks on finished surfaces. Fluids should be changed more often than is customary in grinding steel.[2,9,10]

3-2.1.7 Recommended Techniques and Inspection

Titanium and titanium alloys have similar grinding characteristics, except that the former may give a little better wheel life. In both cases, there is a very limited operating range; hence, care must be taken to establish rather precise grinding conditions.

The following recommendations are reviewed in order to provide the good grinding conditions needed for titanium:

(1) High-quality grinders with variable-speed spindles
(2) Rigid setup of work and wheel
(3) Rigid mechanical holding fixtures
(4) Arbors for external grinding
(5) Oxidized machine centers to prevent galling of small parts
(6) Backing whenever necessary to overcome deflection of the work.

Wheel grades should be chosen, using the following suggestions as guides:

(1) The largest practical diameter and width of wheel should be used
(2) Grits should possess the characteristics of progressive intergranular chipping as flat spots develop by attrition
(3) The abrasive grain should be of optimum size; smaller sizes allow whole grains to leave the wheel prematurely, resulting in higher wheel gear
(4) The hardest wheel that will not cause burning or smearing should be used
(5) Vitrified materials are best in that they are more porous, permit better swarf clearance, and result in grinding at lower temperatures.

Adjustments in wheel speed, work speed and feed, truing conditions, and the grinding fluid may compensate for the selection of a wheel with less than optimum characteristics. Troubles originating

*See Section 3-0.1.4 for precautions in the use of chlorinated oils.

TABLE 3-2.1.3-2. CHART OF MARKINGS ON GRINDING WHEELS

Abrasive Symbols[a]		Grit Size				Grain		Wheel Grade			Structure				Manufacturer's
Silicon Carbide	Aluminum Oxide	Coarse	Medium	Fine	Very Fine	Combination		Soft	Medium	Hard	Dense	Medium	Open	Bond Types	Symbols
5C	A	10						A			0			V = vitrified	Modification of bond[b]
6C	2A	12	36	90	240	1	Coarse	B			1	5	9	R = rubber	
CA	97A	14	46	100	280	2		C			2	6	10	B = resinoid	
C2A	4A	16	54	120	320	3		D	I		3	7	11	E = shellac	See manufacturers' brochures
C4A	9A	20	60	150	400	4		E	J		4	8	12	M = metal	
7C		24	70	180	500	5		F	K				13	S = silicate	
		30	80	220	600	6		G	L	Q			14		
						7	Fine	H	M	R			15		
									N	S			16		
									O	T					
									P	U					
										V					
										W					
										X					
										Y					
										Z					
A typical marking sequence	2A		60			1 - K					6 - VL				

Description of Various Grades of Silicon Carbide and Aluminum Oxide Abrasives[a]

C - Silicon Carbide

- 5C - Green silicon carbide
- 6C - Black silicon carbide
- CA, C2A, C4A } Mixed aluminum oxide and silicon carbide
- 7C - Mixed silicon carbide

A - Aluminum Oxide

- A - Tough aluminum oxide
- 2A - Semifriable
- 97A, 4A } Friable
- 9A - Very friable (white)

(a) Cincinnati Milling Machine Company nomenclature.

(b) Some manufacturers also add a number designating whether the wheel grade is either exact, 1/3 softer or 1/3 harder than the better grade indicated (K in the example shown).

from resonant vibrations can usually be corrected by improved jigs or by backing up thin, slender sections to prevent deflection.[2]

Grinding operations should be supervised and controlled very carefully. The recommended procedures should be followed without substitution.

When the grinding procedure used is questionable, quick checks to indicate possible surface cracking can be made by dye and fluorescent penetrants or etching to indicate surface cracking. However, none of these tests will indicate surface damage that does not involve cracking.

Care must be exercised when a 1-minute etch with 10 percent HF is used to reveal cracks. Improper etching treatments and etching solutions can cause cracks, since surfaces already may be damaged by residual tensile stresses.

Each operation should be inspected to ensure that it is performed with due regard for the safety of the personnel involved.

Wheels used to grind titanium and its alloys must be dressed more frequently than those used to grind steels because of the tendency of titanium to load the wheel. This causes higher temperatures at the wheel-metal interface, which tends to produce surface crakcs, and in some cases to burn the metal.

Some ground parts must be stress relieved by heat treatment prior to final inspection. A common stress relief is to heat the part at 1000 F for 1 hour in a neutral atmosphere to avoid contamination.

Data on speeds and feeds for both silicon carbide and aluminum oxide grinding wheels are shown in Table 3-2.1.7-1.

3-2.2 ABRASIVE BELT GRINDING

3-2.2.0 Introduction

An unusual combination of chemical and physical properties makes titanium more difficult to grind with abrasive belts than most common metals. The surface of titanium may become hardened by reaction with oxygen and nitrogen in air at the high temperatures reached in grinding. At the same time, the metal tends to weld to the abrasive grains of the belt. The ultimate result is poor belt life -- either through an accelerated fracture rate of the abrasive grains or through rapid dulling as the cutting edges become "capped" with titanium. "Capped" grains function as flat bearing areas, which slide over the titanium surface, creating additional frictional heat without accomplishing any useful cutting. This characteristic, combined with the low thermal conductivity of titanium, frequently causes burning of the ground surfaces.

Successful grinding of titanium with abrasive belts depends on minimizing the oxygen and nitrogen reaction and also the tendency for welding. Both can be accomplished by lowering the temperature at the grinding point through adequate cooling and by using a grinding fluid that will inhibit the chemical reaction between the abrasive and titanium. Successful grinding also requires controlled "fracture wear" of the abrasive grit in order to supply constant sources of fresh cutting edges during grinding. This can be promoted through the proper choice and combination of abrasive materials, grit size, contact wheel, belt speed, and work feed.

Titanium sheet can be belt ground to close dimensional tolerances. Belt grinders have produced flat surfaces with only 0.004-inch maximum deviation over areas up to 36 x 36 inches. The cost of grinding titanium is estimated to be 6 to 10 times that for stainless steel.[5,10,16-18]

3-2.2.1 Equipment and Setup

The carrier-type machine is usually used in the abrasive-belt grinding of sheet. The work is held on a table that oscillates back and forth under grinding belt. A Billy-roll directly under the contact roll maintains the pressure between the work and the belt.

Machine rigidity is important for achieving close dimensional tolerances.

3-2.2.2 Selection of Abrasive Belts and Contact Wheels

Abrasive size, belt backing, and type of bond are important factors to consider when choosing an abrasive belt.

Roughing and spotting operations are normally carried out on belts coated with medium- or fine-grain-abrasives (40 to 80 grit); Grit 80 is slightly superior to Grits 40 and 60. Extra-fine-grain abrasives (Grits 120 to 220) are used for finish belt-grinding operations.[19]

Three types of belt backings are used for abrasive-belt grinding of titanium. They include paper-backed, cloth-backed, and fully water proof cloth-backed belts.

Paper-backed belts, used dry or with suitable grinding oil, can be used for some flat sheet work. Cloth-backed belts are used when a more rugged backing is needed. Fully waterproof cloth-backed belts are necessary when water-base grinding fluids are used. Cloth belts are generally available in two types: drills (X-weight), which

TABLE 3-2.1.7-1. PRECISION GRINDING OF TITANIUM AND ITS ALLOYS[a]

Abrasive Material[b]	Silicon Carbide		Aluminum Oxide	
Abrasive types	Regular; green		Special friable, white	
Grit size	Medium (60-80)		Medium (60-80)	
Wheel grade (hardness)	Medium (J-K-L-M)		Medium (J-K-L-M)	
Structure	Medium (8)		Medium (8)	
Bond[c]	Vitrified (V)		Vitrified (V)	
Operation[d]	Roughing	Finishing	Roughing	Finishing
Feed				
Down feed, ipp	0.001[e]	0.0005[f]	0.001[e] 0.0005	0.0005[g]
Cross feed, inch	0.062 0.050[h]	0.05 0.025[h]	0.05 0.10	0.05
Speeds				
Table, ipm	300-500	300-500	300-500	300-500
Wheel, sfpm	2500-5000	2500-4000	1500-2500	1500-2500
Grinding fluids	Highly chlorinated oils or sulfochlorinated oils (do not dilute). Possible fire hazard; hence, flood the work.		Rust-inhibitor types[i] present no fire hazard. Oils used for silicon carbide wheels also have been used with very little fire hazard, since the low speeds involved generate very little sparking and oil mist.	

(a) From References (1), (3), (5), (6), (9-15).
(b) Equipment considerations are primary in abrasive selection. If only conventional speeds are available, generally, aluminum oxide is not recommended; if low speeds are available, aluminum oxide is superior. Silicon carbide wheels are used for solution-treated and aged alloys.
(c) Particular modification of vitrified bond does not seem to matter with titanium.
(d) Type wheels which have been used include 37C80-L8V and 32A60-L8VBE.
(e) Use this down feed to the last 0.001 inch, with two passes of 0.0005 ipp thereafter, and then spark out.
(f) For surface finishes better than 25 microinches rms, the downfeed should be less than 0.0002 ipp on the last pass, and then spark out.
(g) The last 0.003 inch should be removed in steps not to exceed 0.0005 ipp. The final two passes should be at zero depth (spark out).
(h) Recommended for B120VCA, using green silicon carbide wheels.
(i) 10:1 and 20:1 concentrations of potassium nitrite have been used. The operating advantages of the latter appear to offset the slight increase of grinding efficiency of the former.

are the heavier and stiffer of the two, and jeans (J-weight).[20,21] The flexible J-weight backing is used for contour polishing; the X-weight provides the best belt life and fastest cutting.

All belts are usually manufactured to close tolerances on thickness to permit grinding to precise dimensions.

Synthetic-resin bonds provide maximum durability for belts used on titanium. They are available on either a waterproof or nonwaterproof backing.

Proper choice of contact wheels is also important in belt grinding. These wheels support

the belt and, hence, govern the action and effective penetration of the abrasive grains during the grinding operation. This action has been termed "aggressiveness" - or the ability of the wheel to make the belt cut. (20,21)

Two types of contact wheels are in use: plain-faced and serrated. A plain-faced wheel puts all the abrasive wear on one plane and produces a flat, ground surface. A serrated contact wheel has a series of lands and grooves angled across the wheel. This arrangement gives the unique effect of "sharpening" the mineral grains as they undulate over the face of the wheel. The relation between the lands and the grooves -- and the angle at which they cross the face of the wheel -- determines to a great extent the cutting rate of the wheel.

Plain-faced wheels are normally used for titanium when unit pressures are high enough to foster the necessary breakdown of abrasive material for best grinding action. They usually produce a better surface finish than do most serrated wheels. They minimize extreme shelling* or mineral-loss problems. They also permit off-hand grinding and polishing of curved and contoured parts.

The contact wheel should be small in diameter and as hard as practicable. This combination provides almost a line contact and hence, a high unit pressure between the abrasive grits and the work.

Suitable contact-wheel materials for titanium include rubber, plastic, or metal. Rubber is usually recommended because metal contact wheels show little significant increase in stock removal and grinding rate at the price of considerable noise, vibration, poorer surfaces, and higher power consumption. (5)

Rubber contact wheels are available in various degrees of hardness, measured in terms of Durometer units. These [illegible]es may range from 10 (sponge rubber) to about [illegible] rock hard). The softest rubber (other than sponge) has a value of 20. The harder the contact wheel, the faster an abrasive belt will cut and the coarser the surface finish becomes. Softer wheels produce better surface finishes. However, even soft wheels become effectively harder as spindle speeds increase and they present more support to the belt. Softer rubber wheels can be used for blending and for spotting operations to remove isolated defects.

The best contact wheel is one that is firm enough to give restricted contact and good penetration by the grit but resilient enough to eliminate shelling failure of the belt at the highest feasible load. (20-22)

3-2.2.3 Abrasive Belt Materials

Coatings of silicon carbide give the best results under normal feeds. These belts must possess a dense texture (closed coat). Aluminum oxide abrasive belts are usually recommended when very heavy feeds are used. (5)

3-2.2.4 Feed Pressure Requirements

Feeds in belt grinding are controlled indirectly by adjusting the pressure. The correct feed should allow the necessary "fracture wear" of the grains, proper "shelling" of the belt, and effective grain penetration for an economical rate of cut. Under these conditions, metal particles will not clog the belt, and the continual formation of new cutting points on the grains will permit uniform stock removal.

Feeds should be held constant to give the best dimensional tolerances. When feed pressures are increased, it may be advisable to use a softer contact wheel.

3-2.2.5 Grinding Speed

Speed is important to the rate of cutting, belt life, and desired surface finish. Low belt speeds reduce temperature at the grinding point and consequently retard oxidation and welding between the metal and abrasive grains. The tendency toward surface scorching or marring by incandescent chips is also reduced.

The optimum speed to be chosen will depend on the contact wheel, grit size, and work thickness. A speed of 1500 fpm generally gives good results. (5)

A definite correlation exists between optimum grinding pressure and belt speed. Higher speeds require less pressure and vice versa. Feed pressures between 80 and 120 psi have been used, depending on the speed. (13)

3-2.2.6 Grinding Fluids

Lubrication is a most significant factor in abrasive belt grinding. Dry grinding, except for certain intermittent operations (blending, spotting, etc.), is not recommended because of the fire hazard. (5,16,19)

A grinding fluid should be used when taking continuous cuts over fairly large areas. It reduces grinding temperatures and quenches the intense sparking that occurs when titanium is ground.

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*Shelling is the tendency for the abrasive grains on the abrasive belt to loosen and flake off.

Because of the extremely hot sparks formed by titanium, only those grinding oils possessing high flash points (above 325 F) should be used. They should be applied close to the grinding point for rapid spark quenching.

Chemically active organic lubricants may prove superior in finishing operations, provided the fire hazard can be minimized.

With waterproof belts, water-base fluids containing certain inorganic compounds and rust inhibitors show good results. They reduce the fire hazard of titanium dust. Aqueous-solution lubricants seem to give the best performance in grinding setups where high loads are used (Stock removal operations). The following water-base fluids have been used:

- Sodium nitrite (5 percent solution)
- Potassium nitrite (5 percent solution)
- Sodium phosphate* (up to 12 percent solution)
- Potassium phosphate* (up to 30 percent solution)

Soluble-oil emulsions in water are normally poor grinding fluids for titanium but can be used where the alternative is to grind dry at speeds greater than 1500 fpm.

Grinding fluids can be applied by spray or belt immersion techniques.

3-2.2.7 Grinding Techniques and Inspection

When titanium is to be belt ground, a roughing operation is usually made, using a 50-grit belt to remove gross surface imperfections. An intermediate grind (80 grit) is then used to reduce the grind marks, followed by a finishing operation using a 120-grit belt.[19]

The correction of belt troubles requires an understanding of glazing and loading. Glazing occurs on abrasive belts when the grinding pressure is insufficient to break down the abrasive particles properly. A loaded belt contains smeared metal welded to the grains, a condition which impairs cutting ability. Proper lubrication is one way to prevent loading.[2,21]

The same inspection procedures recommended in the precision grinding section also apply to belt grinding.

Table 3-2.2.7-1 summarizes the pertinent data required for the abrasive belt grinding of titanium and its alloys.

3-2.3 ABRASIVE SAWING

3-2.3.0 Introduction

Titanium is difficult to cut with abrasive wheels. In fact, it is practically impossible to plunge straight through a large piece of titanium. Wheel loading causes high residual stresses on the cut surfaces, and stress-relief treatments may be necessary to prevent delayed cracking of cut surfaces.[23,24] When proper techniques are used, however, the cut surfaces can be bright, smooth, and square. Surface finishes between 10 and 14 microinches rms can be obtained.[2,5]

3-2.3.1 Abrasive Cutoff Machines

Rigid setups and abrasive cutoff machines having wheel heads capable of oscillating and plunging motions are recommended. It is also advisable that the cutoff machine be equipped with hydraulic feed mechanisms that can be set to produce any desired cutting rate.[2,5]

3-2.3.2 Abrasive Cutoff Wheels

The choice of the right combination of abrasive grit, wheel hardness, and type of bond will do much to alleviate difficulties. These characteristics are identified for cutoff wheels in much the same way as that shown in Table 3-2.1.3-2. The medium grit sizes of 46 and 60 are usually used.

Wheel grade "L", which is the hardest grade in the soft range, and the "M" which lies in the medium hardness range, are the most applicable.[2]

3-2.3.3 Abrasive Materials

Silicon carbide cutoff wheels are generally used on titanium; aluminum oxide wheels do not seem to be satisfactory.[5] Rubber-bonded, silicon carbide Type 37C and its equivalent seem to give the best results.[2]

3-2.3.4 Feeds

Successive overlapping of shallow cuts should be taken in order to keep the work-wheel contact area as small as possible at all times. Feeds between 2 and 6 in.^{2}/min are used, depending on setup conditions and wheel speed.[2,5,9]

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* The phosphate solutions are quite caustic and are excellent paint removers. The more concentrated solutions, however, are not much worse that the 5 percent solutions in these respects and are considerably more effective as grinding lubricants. Care also must be exercised when potassium nitrate is used as a fluid because the dry salt may become a fire hazard.

TABLE 3-2.2 7-1. ABRASIVE-BELT GRINDING OF TITANIUM AND ITS ALLOYS[a]

	Spotting	Roughing	Finishing[b]
Belt Characteristics			
Abrasive Grit Size	40 to 80 (1-1/2 to 1/8)		120 to 220 (3/0 to 6/0)
Belt Backing	E (paper) X (cloth)		E (paper) X (cloth)
Coating Texture	Closed[c]		Closed[c]
Bond	Resin		Resin
Grinding Variables			
Grit Size[d]	40 to 80 (1-1/2 to 1/8)	80	120 to 220 (3/0 to 6/0)
Speed, fpm	1000 to 1500	1500[c] to 2200	1500[c] to 2200
Feed, psi[e]	--	120 to 80	120 to 80
Depth of Cut, inch		0.002	0.002
Table Speed, fpm	--	10	10
Grinding Fluids	No	Yes	Yes
Grinding Fluids			
For Paper Belts	Heavily sulfurized chlorinated oils (flash point: 325 F or higher).		
For Cloth Belts	A 10 percent nitrite-amine rust inhibitor, water solution, or a 5 percent potassium nitrite solution[f]. Fifteen percent solutions of trisodium or potassium phosphate also have been used.		

(a) From References (5), (10), (18), (19), and (22).
(b) In finishing operations with fine grits, a light pressure is required to prevent shelling. A dull belt (but cutting well) often produces a finer finish than a new, sharp belt of the same grit.
(c) Preferred.
(d) Fine grits tend to fail by shelling at pressures that coarser grits will easily withstand.
(e) Feed pressure is inversely proportional to speed.
(f) When potassium nitrite is used the safety precautions described previously should be followed.

3-2.3.5 Cutting Speed

Speeds from 6800 to 12,000 fpm have been used successfully in abrasive cutoff operations.(2,5,9)

3-2.3.6 Cutting Fluids

A rust-inhibitor type of coolant should be supplied at the rate of about 20 gal/min to the work-wheel contact area in order to reduce cutting temperatures enough to avoid heat cracking of the cut surfaces.

The coolant should penetrate to the wheel-work contact area. It should be applied equally to both sides of the wheel to avoid cracked cuts and wheel breakage.

Soluble-oil coolants can be used, but they have a tendency toward foaming. Soluble-oil coolants are available that minimize the objectionable rubber-wheel odor.(2)

3-2.3.7 Cutoff Techniques

The size of the workpiece influences the choice of cutting techniques. Small stock can be cut without an oscillating head or rotation of work. Bars from 1 to 3 inches in diameter may require either an oscillating or a nonoscillating wheel. Both should be tried in order to determine which is better for the given situation.

Bars larger than 3 inches in diameter usually require rotation of the work as well as an oscillating wheel. The work should be rotated slowly, or indexed, so that the wheel can cut toward the center without cutting too far beyond center.[2,5,25]

The choice of speeds and feeds depends on the diameter of the work and the mode of cutting (oscillating, nonoscillating, work rotation). Some combinations that have given satisfactory results are presented in Table 3-2.3.7-1.

It may be desirable to stress relieve the workpiece by heat treatment for 1 hour at 1000 F after cutting. Whether the treatment is necessary or not can be checked by inspecting the cut surfaces with dye or fluorescent penetrants when cracks are suspected.[2]

TABLE 3-2.3.7-1. ABRASIVE SAWING OF TITANIUM AND TITANIUM ALLOYS[a]

Workpiece Cross Section, in.^{2}	Typical Wheels Used[b]	Wheel Diameter, inch	Cutting Rate in.^{2}/min	Wheel Speed, fpm	Cutting Fluid
Up to 3	37C90-NOR-30 37C60-POR-30	10	2 to 3	9,500	Water-base or Cambelline solution (1:50)
3 to 5	37C46-MOR-30	16	2 to 3	9,500	
Up to 5	37C601-L6R-50 37C601-I4R-50	16	3 to 4	12,000	10 percent nitrite amine solution at 20 gal/min
Up to 7	C60-NRW-3 C60-NRL	20	2.5 to 3	7,300	Water-base or cambelline solution (1:50)
7 to 80	C60-NRW-3 C60-NRL	26	5 to 6	6,800	Water-base or cambelline solution (1:50)

(a) From Refs. 2,5,25-28.
(b) The "37C" wheels are Norton designations; the "C" wheels are Allison designations.

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3-3 Unconventional Machining

3-3.0 INTRODUCTION

The need for fabricating or shaping parts from hardened high-strength and heat-resistant metals and alloys has created new and difficult machining problems for industry. The conventional or traditional machining methods, which utilize the shearing action of a sharp tool against the workpiece to achieve chip-by-chip metal removal, are not very efficient against some of the new tough and hard materials. To meet these difficult machining and metal-removal problems, new or improved metalworking methods were needed.

Among the new nonmechanical metalworking processes or methods developed for machining accurate and complex shapes from tough metals and alloys are electrochemical machining, chemical milling, electric-discharge machining, electron-beam machining, ultrasonic machining, and laser machining. The following subsections of the handbook deal with the first three of the above methods, respectively, with particular emphasis being placed on the machining and shaping of titanium alloys. Electrochemical machining and chemical milling are currently both being widely used in the aircraft industry for processing titanium alloys, whereas electric-discharge machining is being utilized on a more limited basis.

3-3.1 ELECTROCHEMICAL MACHINING

3-3.1.0 Introduction

In electrochemical machining (ECM), metal is removed from a workpiece without arcs, sparks, or high temperatures by passing a direct current between the workpiece (anode) and the shaped tool or tools (cathode) through a suitable electrolyte. Metal removal is by electrochemical dissolution or reaction. The rate of metal removal is directly proportional to the applied current and is in accordance with Faraday's laws. For a general discussion of ECM, see References (1) through (4).

ECM can be likened to an electroplating process operating in reverse. In ECM, the primary interest is in removal of metal at the anode (workpiece) rather than in the deposition of metal on the cathode as in electroplating. The high velocities of electrolyte flow (20 to 250 ft/sec) in ECM, together with the close spacing (0.001 to 0.040 inch) of the electrodes, permit the passage of high currents at relatively low voltages (e.g., 3 to 25 volts), resulting in high rates of metal removal. For example, current densities of 40 to 1500 amp/in.^{2} or more are common for ECM, whereas current densities of 0.1 to 2.5 amp/in.^{2} are typical of most plating operations. Electrolyte pumping pressures for ECM generally range from about 20 to 450 psi.

Figures 3-3.1.0-1 and 3-3.1.0-2 illustrate the workings of the ECM process and indicate typical operations that can be performed. ECM drilling is shown in Figure 3-3.1.0-1.

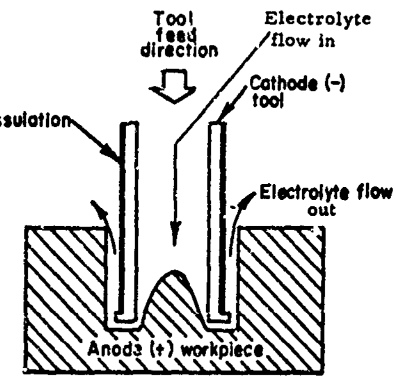

FIGURE 3-3.1 0-1. ECM-DRILLING OPERATION

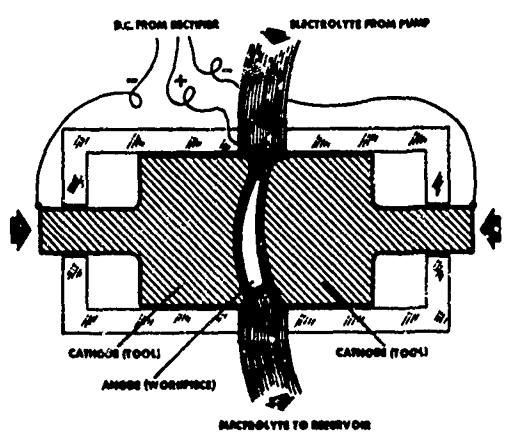

FIGURE 3-3.1.0-2. BLADE-ELECTROSHAPING OPERATION

At the start, the drilling tool is brought to the desired gap distance (e.g., 0.002 to 0.015 inch) from the titanium-alloy workpiece. Voltage is then applied, causing current to pass through the electrolyte. As the drilling operation proceeds, the workpiece dissolves and the tool is steadily advanced to maintain a constant machining gap. The drilling tool shown is insulated on the outside to minimize side cutting and to help produce a hole with a straight bore.

A schematic representation of blade electroshaping is shown in Figure 3-3.1.0-2. The rough forging is positioned between shaped electrode tools in a specially designed plastic fixture. Electrolyte is pumped under pressure into the spaces between the electrodes and the workpiece. As ECM proceeds and the workpiece dissolves, the electrodes are moved in simultaneously to maintain a relatively constant machining gap. This operation continues

until the blade has the desired configuration, as set by the cathode tools and the operating conditions.

The general procedures described above can be used for trepanning, die-cavity sinking, broaching, and other contouring or shaping operations. Three-dimensional cavities can be produced readily by ECM using a single-axis movement of the shaped tool electrode. For cavity-sinking and contouring work, the electrolyte flow path is often of the flow-past type (i. e., electrolyte flow is roughly parallel to the electrodes) shown in Figure 3-3. 1. 0-2, rather than the flow-through type shown in Figure 3-3. 1. 0-1. Since no drilling-tool rotation is needed, ECM is especially suited for drilling multiple holes. Also, irregularly shaped holes can be produced readily by ECM.

3-3. 1. 1 Equipment

Figure 3-3. 1. 1-1 shows a typical general-purpose ECM installation.[5] The unit shown can be used for cavity sinking, drilling, trepanning, contouring, broaching, and other ECM operations. The installation illustrated is in the 5,000 to 10,000-ampere class.

ECM units with current capacities ranging from 100 to 19,000 amperes are available commercially. Units with 10,000-ampere capacities are currently used in industry. Larger units, with ratings of 20,000 amperes and more, are being planned and should be in operation soon.

3-3. 1. 2 Tooling and Fixturing

The ECM cathode tool(s) usually conform closely to the reverse image of the shape to be produced. Detailed information on design of cathode tools is proprietary and has not been generally disclosed. The results of some work on a computer-program approach to tool design has been reported.[6,7]

ECM electrodes are usually made of copper, brass, stainless steel, copper-tungsten alloys, or other conductive and corrosion-resistant materials. Specially designed fixturing is usually needed to provide good controlled electrolyte flow to the electrodes for efficient and accurate ECM operation. The The tooling and special fixturing used in the ECM sinking of waffle-grid pockets in titanium-alloy plates are shown and discussed later.

Tooling costs for certain types of ECM operations can be rather expensive. For that reason, ECM is generally better suited to production work than to single or small-lot jobs, unless, of course, the unique capabilities of ECM justify the cost of using the process for machining small lots of hard-to-machine metals or shapes. For production work, the fact that the tool does not wear, erode, or change during ECM is very advantageous. It means that once a suitable tool is developed, it can be used or reused indefinitely to produce replicate parts, without any need to compensate for tool wear.

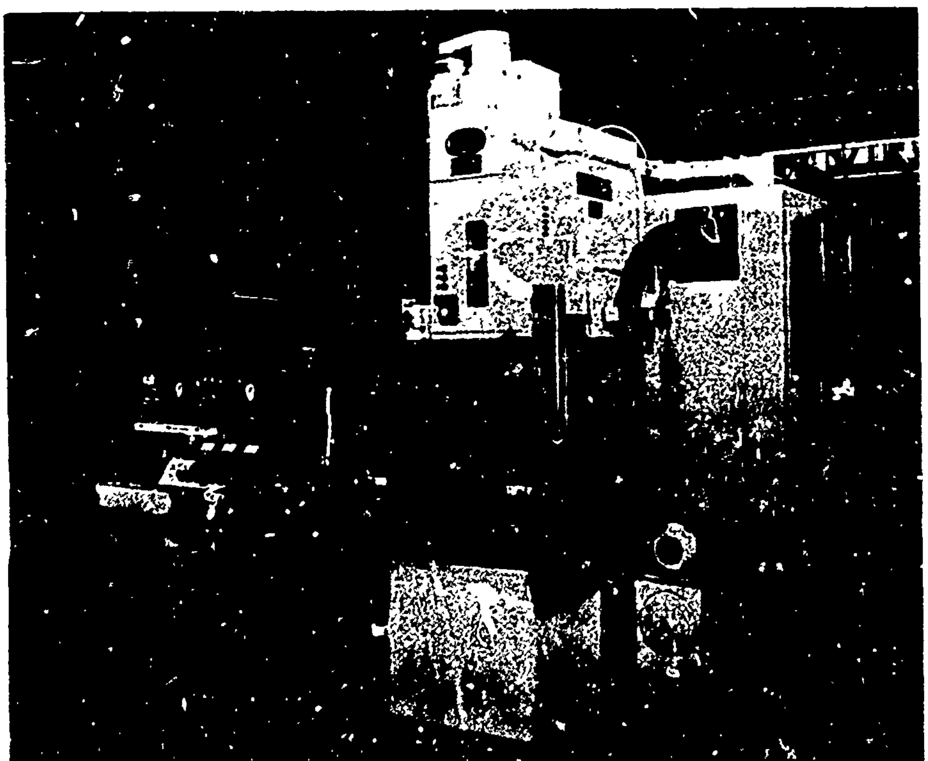

FIGURE 3-3. 1. 1-1. GENERAL-PURPOSE ELECTROCHEMICAL-MACHINING INSTALLATION[5]

3-3. 1. 3 Electrolytes

Electrolyte compositions, operating conditions, together with the chemistry and microstructure of the particular titanium alloy being processed, are important in determining how effectively ECM will cut and also the quality of the surface finishes produced. Specific information on electrolytes for machining various titanium alloys is mostly proprietary and has not been generally disclosed. Electrolyte formulations based on the use of sodium chloride plus other salts or materials have been used to machine titanium alloys. Some specific data on electrolyte compositions are presented later. Proprietary formulations for ECM of specific titanium alloys as well as other metals and alloys are c.. the market.

3-3. 1. 4 Metal-Removal Rates and Tolerances

Figure 3-3. 1. 4-1 shows penetration or metal-removal rates for ECM of titanium and other metals at various current densities. The rates are theoretical for metal dissolution at 100 percent anodic-current efficiency in the valence states indicated. ECM dissolution efficiences are generally high, and usually range from about 90 to 100 percent.

Typical feed rates for cavity-sinking, blade-shaping, and contouring operations range from about 0. 005 to 0. 150 inch or more per minute. Penetration rates for drilling operations are usually higher and range from about 0. 030 to 0. 500

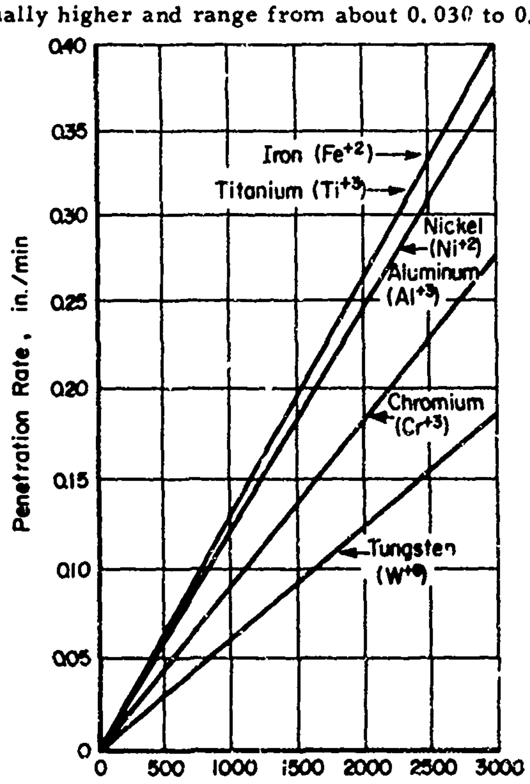

FIGURE 3-3. 1. 4-1. PENETRATION RATES FOR TITANIU'. AND OTHER METALS

in. or more per min. Broaching or planing operations can be performed at rates of 1 to 5 in. or more per min, with removal of about 0. 010 to 0. 050 in. of metal (depth of cut) from the surface.

Tolerances in ECM depend upon the type of operation being carried out. Hole diameters can be machined to ±0. 001 in. Tolerances for other shapes can range from about ±0. 002 in. to about ±0. 030 in. , depending on configuration and the particular type of ECM operation involved.

3-3. 1. 5 Operating Conditions

As indicated earlier, much of the specific data and information on electrolyte compositions and operating conditions for ECM of titanium alloys is proprietary and has not been publicly disclosed. However, some of the data and information that are available on electrolytes and operating conditions are presented and discussed below. Typical operating data on ECM sinking of square pockets in annealed Ti-6Al-4V alloy plates to produce waffle-grid panels are given in Table 3-3. 1. 5-1. Figure 3-3. 1. 5-1 shows a typical panel with 18 pockets sunk by ECM.

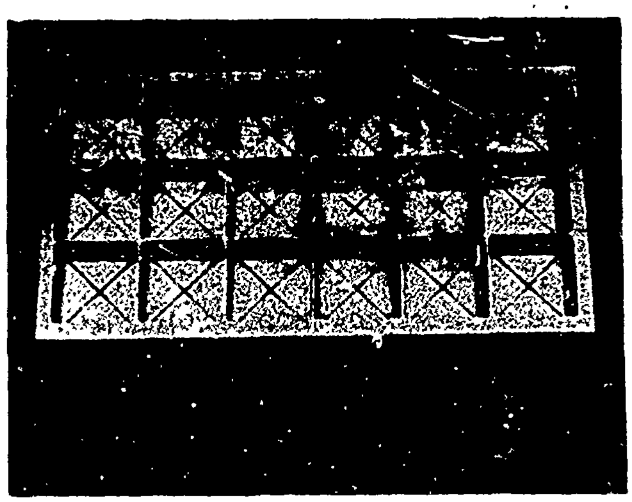

FIGURE 3-3. 1. 5-1. Ti-6Al-4V ALLOY WAFFLE-GRID PANEL PRODUCED BY ECM[6]

The cathode tool and other ECM fixturing used to sink the pockets are shown in Figure 3-3. 1. 5-2.

A reverse electrolyte flow system was used in this operation. The electrolyte was pumped into the plastic dam from where it flowed between the workpiece and the cathode tool and then out through the X-like opening in the cathode tool (see Figure 3-3. 1. 5-2). The cathode tool was copper, with a copper-tungsten alloy tip.

The pockets in the panels were sunk one at a time using a 10,000-ampere horizontal machine.

TABLE 3-3. 1. 5-1. REPRESENTATIVE OPERATING CONDITIONS AND SURFACE ROUGHNESSES FOR SINKING WAFFLE-GRID POCKETS IN TITANIUM ALLOY PANELS[6]

Note: Pockets were sunk in annealed Ti-6Al-4V alloy panel. The finished pocket dimensions were 2. 3 x 2. 3 inch square and 0. 925 inch deep.

Electrolyte	Sodium chloride (NaCl) in water
Electrolyte Concentration, lb/gal	1. 0
Electrolyte Temperature, F	115 - 125
Electrolyte Pressure, psig	180 - 200
Applied Voltage, volts	13
Current, amp	2400
Current Density, amp/in. ^{2}	480
Feed Rate, in. /min	0. 050
Machining Gap, in.	0. 008
Electrode Overcut at Sides, in.	0. 030
Pocket Depth, in.	0. 925
Machining Time/Pocket, min	18. 5
Surface Roughness, microinches	
Bottom of Pockets	22 to 28
Sides of Pockets	120 to 140

FIGURE 3-3. 1. 5-2. CATHODE TOOL AND OTHER ECM FIXTURES[6]

Left: Cathode-tool holder
Center: Cathode tool
Right: Electrolyte dam

The panels were mounted vertically in the machine with the cathode travelling in the horizontal direction. Machining time was 18. 5 minutes/pocket. The time for indexing the panel, checking the cathode tool, and rapid traversing of the cathode tool was about 1. 5 minutes. This results in a total time of 20 minutes/pocket. As can be seen from Table 3-3. 1. 5-1, only 2400 amperes, or less than 1/4 of the 10,000 amperes available from the unit were utilized in sinking the pocket in the experimental work. Thus, in a production operation it should be possible by using the full capacity of the unit to machine four pockets simultaneously or two pockets at twice the feed rate given in Table 3-3. 1. 5-1. This would result in an overall machining time of about 5 minutes/pocket.

Surface roughness of the ECM'd pockets was 22 to 28 microinches on the bottom and 120 to 140 microinches on the side. The values compare to NC-milled (numerically controlled mechanically milled) surfaces of 25 to 60 microinches on pocket bottoms and 50 to 80 microinches on the sides. The rough surfaces of the pocket sides were attributed to low current density etching to the rear of the cathode tip as the cathode advanced into the plate.

At the pocket bottom, where the current density was high (about 480 am/in ^{2}), smooth surfaces were produced. The small diagonal ribs, shown in the bottoms of the pockets in Figure 3-3. 1. 5-1, were formed by the 1/32-inch-wide electrolyte slots in the face of the cathode tool.

It was concluded from this work[6] that ECM appeared to be a practical production method for producing waffle-grid panels with riser intersection radii as small as 0. 060 inch at about the same cost as NC milling with 0. 250-inch corner radii. With the waffle-grid panel configuration used in this study, ECM'd panels showed a weight saving of 0. 20 lb/ft^2 over NC-milled panels. The tolerances that were expected to be held for the ECM'd panels were riser thickness variation of 0. 004 inch and skin-thickness variations of 0. 004 inch.

ECM'd waffle grid panels, as well as NC-milled panels, did not show evidence of fatigue cracking when subjected to simulated high-speed flight conditions. However, specimens cut from the ECM'd riser material showed about 25 to 30 percent lower fatigue strength than did corresponding NC-milled specimens when subjected to constant-amplitude testing. Since specimens cut from the ECM pocket bottom or skin material exhibited about the same fatigue strength as corresponding NC-milled specimens, it appears that the relatively rough surface finish of the ECM risers is probably the cause of the lower fatigue strength

Representative operating data from other work on trepanning of exemplary parts in Ti-8Al-1Mo-1V alloy with a NaCl electrolyte are given in Table 3-3. 1. 5-2. Blade-like projections (about 4 inches long, 1. 2 inches wide, and about 0. 2 inch thick at the center) were trepanned from rectangular bars. Surface-roughness data on the ECM'd parts are also given in Table 3-3. 1. 5-2. The relatively high surface-roughness values on certain areas of the Ti-8Al-1Mo-1V parts were attributed to machining at low current densities. It should be kept in mind that the surface-roughness data given in Table 3-3. 1. 5-2 are for exemplary parts machined with a particular set of operating conditions and do not necessarily indicate the best surfaces that might be obtained with different operating conditions and different types of ECM operations.

In later experimental work[8,9], good smooth surfaces (20 microinches AA or less) were produced on Ti-8Al-1Mo-1V alloy pieces over a wide

range of ECM operating conditions (e.g., gap distances of 0.005 to 0.020 inch, electrolyte velocities of 30 to 70 ft/sec, feed rates of 0.020 to 0.060 in./min) using NaCl-type (composition not disclosed) electrolytes.

Other workers have explored[10] a variety of electrolyte systems for cutting (slicing operation with a single or multiple cut-off wheel) of unalloyed titanium (MST III)* workpieces using a rapidly rotating cathode wheel. From among acidic, neutral, and basic electrolytes, the best results were obtained with an acid-fluoride solution of the following composition:

Hydrofluoric acid (sp gr 1.20)	68 ml/liter
Nitric acid (sp gr 1.42)	107 ml/liter
Hydrochloric acid (sp gr 1.19)	125 ml/liter

TABLE 3-3.1.5-2. REPRESENTATIVE OPERATING CONDITIONS AND SURFACE ROUGHNESSES FOR TREPANNED PARTS OF Ti-8Al-1Mo-1V ALLOY[7]

Note: Rectangular bars of Ti-8Al-1Mo-1V alloy (Rockwell C hardness: 32 to 36) were used as workpieces.

Electrolyte	Sodium chloride (NaCl in water
Electrolyte Concentration, lb/gal	0.8
Electrolyte Tank Temperature, F	103
Applied Voltage, volt	20.0
Current, Start, amp	100
Current, Max, amp	500
Current, End, amp	460
Electrolyte Inlet Pressure, Start[a], psig	205
Electrolyte Inlet Pressure, End[a], psig	265
Electrolyte Exit Pressure, Start[a], psig	50
Electrolyte Exit Pressure, End[a], psig	0
Feed Rate, in./min	0.20
Depth Cathode Ram Travel, in.	4.0
Surface Roughness Data, microinches AA	
Top of blade-like projection	120-200
Root section	120-220

(a) The electrolyte pressures levelled off after the initial 0.1 inch of travel at the end values given in the table.

Typical operating conditions were:

Cathode Wheel Speed	120 surface ft/sec
Voltage	10 to 12 volts
Temperature	70 F ±10 F
Feed Rate	0.32 in./min
Length of Cut	0 to 1.5 in.

With many of the electrolytes evaluated, passivity of the titanium workpieces occurred, and satisfactory cutting at rates above 0.005 in./min could not be achieved.

* Centerless-ground bar stock (1.48 in. diam); 55,000-psi maximum-yield-strength range; annealed 165 Vickers hardness (approximately 158 Brinell).

In other work[11], as-forged compressor blades of Ti-6Al-4V alloy were electrochemically machined with a metal-removal rate of about 0.040 in./min/side using a NaCl-type electrolyte. The electroshaping operation used was similar to that illustrated in Figure 3-3.1.0-2. The ECM surfaces were very smooth, with surface-roughness values of 8 to 12 microinches.

3-3.2 ELECTROCHEMICAL GRINDING

The term electrochemical grinding (ECG) as used herein refers to metal removal by a combination of electrochemical action and mechanical action. ECG might be considered as a specialized form of electrochemical machining. Figure 3-3.2-1 shows a schematic representation of the electrochemical grinding process.

In the operation shown, the conductive wheel (cathode), which may be impregnated with abrasive particles, is rotated against the titanium-alloy workpiece (anode). Metal-bonded diamond, metal-bonded aluminum oxide, and carbon wheels are used for much of the ECG work. The rotation wheel removes the film of solid-type electrolysis products from the workpiece to continuously expose fresh surface, thus permitting electrochemical action to continue. The shearing force of the electrolyte film on the rapidly rotating cathode wheel or the wheel surface removes and carries away the electrochemical reaction products on the workpiece surface.

Generally, about 85 to 98 percent or more of the metal removal in ECG is by electrochemical action, with mechanical abrasion accounting for the remainder. Consequently, the wheel pressures in ECG are much less than those for conventional mechanical grinding, and wheel wear is also less. Because of the lesser wear, ECG wheels will usually last 5 to 10 times, or more, longer than conventional grinding wheels.

Electrolytes for electrochemical grinding usually differ from those used for electrochemical machining (ECM). ECG electrolytes are usually aqueous solutions of salts such as sodium nitrite, sodium nitrate, sodium carbonate, and potassium nitrate, or mixtures thereof, plus special addition agents. Electrolyte formulations aim at providing good surface finishes, good conductivity, good grinding performance, and also at being nontoxic and noncorrosive to personnel, machines, and surroundings. Special proprietary formulations are marketed for electrolytic grinding of titanium alloys and also for most other metals and alloys.

Data and results from a study on electrochemical grinding (abrasion assisted) of Ti-6Al-4V material are given in Table 3-3.2-1.[12] Metallographic examination showed that the ECG'd surfaces were satisfactory. The surfaces were uniform and good in appearance, and were free of pits and intergranular attack.

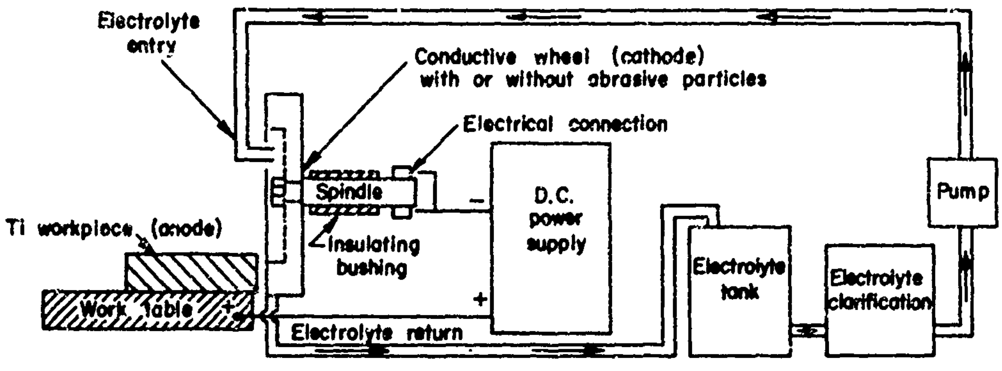

FIGURE 3-3.2-1. SCHEMATIC DIAGRAM OF THE ELECTROCHEMICAL-GRINDING PROCESS

TABLE 3-3.2-1. DATA AND RESULTS OF ELECTROCHEMICAL GRINDING OF Ti-6Al-4V ALLOY[12]

Note: The Ti-6Al-4V material was ground in the mill-annealed condition. Grooves were made in test plates with an electrolytic grinder equipped with an A3HC-60-1/2 metal-bonded aluminum oxide wheel. Full-strength solutions of Anocut No. 90 (Anocut Engineering Company, Chicago, Illinois) electrolytic salts were used.

Item	Value or Comment
Applied Voltage, volts	9.0
Current, amp	150
Depth of Cut, inch	0.010
Feed Rate, in./min	2.0
Return Pass[a]	Yes
Surface Produced	Satisfactory

(a) A return pass indicates feed in one direction and rapid traverse (14 in./min) return to the starting point with current on and electrolyte flowing.

Electrochemical grinding appears to be ideally suited for processing titanium-alloy parts where there might be some danger of surface cracks or heat checks being produced by conventional mechanical grinding. The production of burr-free surfaces, together with the ability to machine thin or delicate workpieces, such as honeycombs, without distortion or heat damage, are additional favorable features of electrochemical grinding.

3-3.3 EFFECTS OF ELECTROCHEMICAL PROCESSING ON MECHANICAL PROPERTIES

Data on the mechanical properties of electrochemically processed titanium alloys are scarce in the published literature. The results of fatigue tests on the electrochemically machined waffle-grid panels were presented and discussed in paragraph 3-3.1.5 above. According to the results of a DMIC study[2,13], electrochemical machining generally has a neutral effect (i.e., produces no significant gain or loss) on mechanical properties such as yield strength, ultimate tensile strength, sustained-load strength, ductility, hardness, etc., for most metals and alloys, including titanium alloys.

Because metal removal in ECM is by anodic dissolution, the titanium-alloy workpieces are not subjected to hydrogen discharge, which occurs at the cathode tool. Thus, there is no danger, in a properly conducted ECM operation, of loss of ductility or delayed fracture of the titanium alloy from hydrogen embrittlement.

Information from the same study further indicated that metals (including titanium alloys) for which mechanical surface treatments or cold working increase fatigue strength, will appear to be weakened about 10 to 20 percent by ECM. The mechanical-finishing methods often impart compressive stresses to the metal surfaces and raise the fatigue strength. In contrast, ECM by removing stressed layers or by forming none, leaves a stress-free surface that permits measuring the true fatigue strength of the metal. The conclusion is that ECM is a safe method to use for metal processing. Where maximum fatigue strength is important, use of a post-ECM treatment, such as vapor honing, bead blasting, or shot peening, is indicated. These subsequent mechanical treatments can restore or impart compressive stresses to the surface, so that ECM parts, thus treated, will exhibit comparable or better fatigue properties than mechanically finished parts.

3-3.4 CHEMICAL MILLING

3-3.4.0 Introduction

Chemical milling generally refers to shaping, fabricating, machining, or blanking of metal parts to specific design configurations by controlled chemical dissolution with suitable etchants or reagents. The process is somewhat similar to the etching procedures used for decades by photoengravers, except that the rates and depths of metal removal are generally much greater for chemical milling.

Much of the early chemical milling was carried out on aluminum and magnesium parts for the aircraft industry. Chemical milling saved on labor, time, and materials. It also provided engineers and designers with an increased capability and flexibility in the fabrication of parts and structures for advanced aircraft, missiles, and space vehicles. During the past 4 or 5 years, use of chemical milling has increased considerably for the production of parts of titanium alloys and other high-strength, thermal-resistant metals and alloys.

Chemical milling is particularly useful for removing metal from the surface of formed or complex-shaped parts, from thin sections, and from large areas to shallow depths. For example, chemical milling has been used extensively for the production of pocketed areas and integral land areas on formed and flat aircraft parts. The weight savings achieved are especially important in aircraft and space-vehicle design. Metal can be removed from an entire part, or else selective metal removal can be accomplished by etching the desired areas while the other areas are masked against chemical attack. Chemical milling can also be used for step etching, tapering, and sizing sheets and plates.

The amount of metal removed or depth of etch is determined by the time of immersion in the milling solution. Simultaneous etching of a part from both sides can be carriet out. In addition to halving the milling time, this procedure also minimizes the danger of warpage due to the release of stresses (if present) in parts. Generally, no elaborate or complex holding fixtures are required for the milling operation. Many parts can be processed at the same time. The production rates, and the size of parts processed, depend mainly on the available tank dimensions and solution volumes.

Some of the technical information on chemical-milling procedures, techniques, and etchant-solution compositions are of a proprietary nature and have not been generally disclosed. *,**

3-3.4.1 Processing Procedures

The overall chemical-milling process consists of four main operations or steps: (1) cleaning or surface preparation, (2) masking, (3) chemical etching or dissolution, (4) rinsing and stripping or removal of the mask. Masking and etching are probably the most critical steps for good chemical-milling results.

3-3.4.1.1 Cleaning

Cleaning of titanium-alloy surfaces is usually done by conventional methods such as wiping or vapor degreasing with chlorine-free solvents and alkaline cleaning to remove all dirt and grease. Where scale, oxidation products, or other foreign materials are firmly attached to the surfaces, molten-salt treatments, acid pickling, or abrasive blasting might be employed to produce a clean surface. Thorough rinsing followed by drying completes the cleaning step. Failure to properly clean the titanium-alloy surfaces can cause masking difficulties and uneven attack of the metal by the etchant solution.

3-3.4.1.2 Masking

Masking for titanium alloys involves the application of an acid-resistant coating to protect those part areas where no metal removal is desired. The mask is usually applied by either dip, spray, or flow-coating techniques The particular method employed depends on part size and configuration.

Vinyl polymers(14) are frequently used as maskants because of their ability to hold up well against the oxidizing acids used in the titanium-etchant solutions. Neoprene elastomers(15) have also been used successfully for masking titanium-alloy parts. Multiple coats (e.g., 3 to 7 or more) are used to provide sufficient mask thickness and good coverage. The intermediate coats are usually air dried. After the final coat, the mask is usually cured by baking at about 200 to 300 F for 1 to 3 hours to improve mask adhesion, tensile strength, and chemical resistance.

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* "CHEM-MILL" is the registered trademark of North American Aviation, Incorporated, which has granted Turco Products, Incorporated, Wilmington, California, the exclusive right to sublicense other firms to use the CHEM-MILL process

** "Chem-Size" refers to a proprietary chemical dissolution process developed by Anadite, Incorporated, South Gate, California, for improving the tolerances of as-rolled sheet and plate, and of parts after forming.

Other desirable characteristics of a good maskant, besides good adhesion and good chemical and heat resistance, are: (1) suitability for accurate pattern transfer on contours and complex configurations -- it must maintain straight lines in the etched design, regardless of its complexity, (2) good scribing qualities, (3) easy removal after scribing to present clean surfaces for etching, and also good stripping after etching to yield clean surfaces for possible subsequent processing, (4) good stability in the liquid form, and (5) economical cost.

Patterns on the masked workpieces are generally applied by means of templates, followed by scribing or cutting of the mask with a special knife, and then manual peeling of the mask to expose the areas to be etched. Mask patterns can also be applied to parts by silk-screen and photographic techniques. These latter techniques are generally used on jobs involving fine details and shallow cuts. Photographic procedures are used to impart and develop the desired pattern on parts covered with a photosensitive resist. Photoresist masks are frequently employed in the blanking or piercing of relatively thin parts (e. g. , thicknesses usually less than about 1/16 -inch), the production of printed circuits, dials, nameplates, etc. , by chemical etching[16].

3-3.4.1.3 Etching

A good etching solution should be capable of removing metal at a uniform and predetermined rate without adversely affecting dimensional tolerances and the mechanical properties of the part. Good chemical stability and the ability to operate effectively over a wide temperature and concentration range are other desirable characteristics of an etching solution. The occurrence of pitting, intergranular attack, uneven etching of the part surface, or the production of rough surfaces are all indicative of an unsatisfactory etchant system or overall chemical-milling operation.

The etchants generally used for chemical milling of titanium alloys are aqueous solutions containing:

(1) $HF-HNO_3$ mixtures
(2) $HF-CrO_3$ mixtures
(3) HF

The exact solution compositions are proprietary. In addition to the main components given above, the solutions may contain special additives to enhance their etching characteristics and inhibit hydrogen pickup. The presence of dissolved titanium-alloy metal in the solutions helps overall etching performance. For that reason, partially aged baths or baths made up by mixing some spent or aged bath with new reagents are generally used.

Parts to be milled are generally immersed in the etchant tanks. The solutions are usually circulated over the workpiece surface to promote uniform metal dissolution. Parts are also periodically moved, turned, or rotated to help achieve uniform metal removal over the entire part surface. For some applications, such as the blanking or piercing of thin parts, the etchants are sprayed against the part. Careful solution-composition and temperature control must be provided to obtain uniform and predictable rates of metal removal.

Typical production tolerances for chemical milling are about ±0. 002 to ±0. 005 inch. To this must be added the actual raw stock tolerance prior to chemical milling.

The following figures can be used as a guide to depth-of-cut limitations for chemical milling[17]:

Sheet and plate	0. 500 inch maximum depth/surface
Extrusion	0. 150 inch maximum depth/surface
Forging	0. 250 inch maximum depth/surface.

Because chemical etching also proceeds sideways at about the same rate as down, the minimum widths that can be machined are about three times the etch depths.

Etch rates for titanium alloys range from about 0. 5 to 5. 0 mils/min. Typical industrial production rates are about 1. 0 to 1. 5 mils/min. A generalized comparison of operating and performance characteristics of etchant systems for milling titanium, steel, and aluminum alloys is presented in Table 3-3. 4. 1. 3-1. Typical surface-roughness values currently being produced range from about 15 to 50 rms microinches[19,20]. These smoother surfaces reflect the results of improvements of some of the earlier work included in Table 3-3. 4. 1. 3-1.

Figure 3-3. 4. 1 3-1 shows a chemically milled Ti-6A-4V alloy panel in which four steps of different depth were produced using a hydrofluoric acid-chromic acid-water etchant. [21] The starting material was 0. 125-inch thick. A multi-scribing

FIGURE 3-3. 4. 1. 3-1. STEP-MILLED Ti-6Al-4V ALLOY SHEET[21]

TABLE 3-3.4.1.3-1. COMPARISON OF DATA AND CHARACTERISTICS OF SYSTEMS FOR CHEMICAL MILLING OF TITANIUM, STEEL, AND ALUMINUM ALLOYS[a]

Item	Titanium Alloys	Steels	Aluminum Alloys
Principal Reagents	$HF - HNO_3$ or $HF - CrO_3$ or HF	$HCl - HNO_3$	NaOH or HCl
Etch Rate, mil/min	0.6 - 1.5	0.5 - 1.3	0.8 - 1.2
Optimum Etch Depth inch	0.125	0.125	0.125
Etching Solution Temperature, F	115 ±10	145 ±5	195 ±5 (NaOH) 110 ±10 (HCl)
Average Surface Roughness, rms microinches	15 - 100	50 - 150	80 - 120 (NaOH) 30 - 60 (HCl)

(a) Data are from Sanz and Shepherd[18] and also from data and information gathered and compiled by the author from other sources.

technique was used; i.e., the parts were masked all over and completely scribed; maskant was then removed from the areas to be etched first (or to greatest depth) and the part was etched; another area of maskant was then removed and the part etched, etc. The thinnest areas are 0.025-inch thick. Tolerances were held to ±0.002 inch.

In other work[22] it was found feasible to chemically blank small details and parts from titanium with material thicknesses up to 0.070 inch. Masking was done using KMER (Kodak Metal Etch Resist, Eastman Kodak Company, Rochester, New York) photosensitive resist. The bath composition used to blank the Ti-8Al-1Mo-1V alloy parts was as follows:

HF	1/2 to 4-1/2 oz/gal
HNO_3	8 to 15 oz/gal
Metal content	0 to 3 oz/gal
H_2O	Balance

Etching was done from both sides simultaneously at 110 to 120 F. Mechanical vibratory stone finishing was carried out on the milled pieces to remove the sharp edges and corners resulting from the blanking operation

A monoacid etchant system containing 10 percent hydrofluoric acid (by volume) has been recently developed.[20] This bath is operated at 104 F, and surface roughnesses of about 40 rms microinches are produced on alloys such as Ti-6Al-4V, Ti-8Al-1Mo-1V, and Ti-6Al-6V-2Sn. The monoacid system should be easier to control and also more economical to operate than systems based on the $HF-HNO_3$, and $HF-CrO_3$ combinations mentioned earlier.

3-3.4.1.4 Rinsing and Stripping

After etching is completed, the parts are thoroughly rinsed with water. The maskant is then either stripped by hand or immersed in a suitable solvent to facilitate its removal. Proprietary solvents are available for handling the various types of maskants used.

3-3.4.2 Hydrogen Pickup During Chemical Milling

Titanium alloys are susceptible to hydrogen pickup during chemical milling. The more important factors governing the amount of hydrogen absorbed are composition and metallurgical structure of the titanium alloy, etchant composition, etchant temperature, and etching time. With some alloys, the amount of hydrogen absorption appears closely related to the amount of beta phase present in the alloy.

The susceptibility of various titanium alloys to hydrogen embrittlement during chemical milling in an $HF-H_2O-CrO_3$ bath has been investigated.[23]

HF	23 percent by volume
H_2O	77 percent by volume
CrO_3	125 g/l.

Bath temperature was 140 F, and etch rate was 1.0 mil/min. Of the three titanium alloys studied, the beta alloy, Ti-13V-11Cr-3Al, was most severely embrittled. The alpha-beta alloy, Ti-6Al-4V, showed some minor embrittlement, whereas the alpha alloy, Ti-5Al-2.5Sn, was not embrittled. Elevated-temperature vacuum treatments were necessary to restore ductility to the Ti-13V-11Cr-3Al alloy. Because of the minor embrittlement, as shown by bend ductility, no embrittlement-relief treatments were evaluated or deemed necessary for the chemically milled Ti-6Al-4V alloy.

Results from various studies on the hydrogen embrittlement of titanium alloys chemically milled in hydrofluoric acid-nitric acid solutions have been summarized.[24] The hydrogen pickup was closely related to the HNO_3-HF ratio in the bath. One study

showed that by maintaining the HNO_3 concentration above 20 percent with 2 percent HF present, the hydrogen pickup could be held to less than 50 ppm for many of the commonly used titanium alloys. However, other investigators reported contrary or different results.

Work elsewhere[25,26] indicated that hydrogen pickup by Ti-6Al-4V material could be satisfactorily controlled in production baths, and that finished parts consistently had less than 150 ppm hydrogen. Additional work was indicated as being required to achieve the same limit of hydrogen in the Ti-8Al-1Mo-1V alloy; the control material had a hydrogen content ranging from 55 to 89 ppm, while the hydrogen content of the chemically milled material was mostly in the range of about 160 to 220 ppm.

With the newly developed monoacid system for milling titanium cited earlier[20], the hydrogen level reportedly could be held in the range of 160 ppm for Ti-6Al-4V and Ti-8Al-1Mo-1V, and in the 200-ppm range for Ti-6Al-6V-2Sn during the etching process, if the initial hydrogen level of the titanium-alloy material is below 100 ppm.

Other investigators[27] have reported that considerable hydrogen pickup was observed in experimental Ti-8Al-1Mo-1V parts, chemical milled at an etching rate of 1 mil/side/min at a temperature of 180 F. The solution contained HF, CrO_3, titanium powder, and dodecyl sulfonic acid. The hydrogen contents before and after are tabulated below:

Material	
As-received sheet	40
Chemically milled from 0.040 to 0.030-inch thickness	360
Chemically milled from 0.040 to 0.010-inch thickness	635

This source indicated that MIL specifications for the Ti-8Al-1Mo-1V alloy allow a maximum 150 ppm, so they would automa ·y reject these sheets. The large hydrogen p up was attributed to operation at the high 180 F temperature. However, low etching rates of 0.1 to 0.2 mil/side/min were obtained when operating at 115 F.

The work discussed above indicates that hydrogen pickup can be a problem in the chemical milling of certain titanium alloys (especially all-beta alloys) under certain operating conditions. Additional research or development work is needed to (1) define and understand the hydrogen-pickup problem; (2) minimize hydrogen pickup by development of better etchant solutions and operating conditions; and (3) develop suitable baking or vacuum outgassing procedure for embrittlement relief.

3-3.4.3 Effects on Mechanical Properties

The general consensus is that chemical milling does not adversely affect the mechanical properties of metals provided good surfaces are produced (i.e., surfaces free of intergranular attack, selective etching, pits, etc.) and that no significant amounts of hydrogen are introduced. Published data, however, on the effects of chemical milling on mechanical properties of metals are rather scarce.

Results from some tensile, compressive, and shear tests[18] showed that chemical milling had no significant effect on these mechanical properties for the Ti-6Al-4V alloy. Chemical milling also had no significant effect on the tensile properties of Ti-5Al-2.5Sn alloy material.[18]

Other work showed that chemical milling did not affect the tensile and ductility properties of heat-treated Ti-7Al-4Mo alloy (see Table 3-3.4.3-1).

TABLE 3-3.4.3-1. TENSILE PROPERTIES OF CHEMICALLY MILLED Ti-7Al-4Mo ALLOY[28]

Note: Longitudinal blanks were cut from Ti-7Al-4Mo forged stock and heat treated to 190,000-psi ultimate strength. The blanks were then machined into standard 1/4-inch-diameter tensile specimens. Allowance was made for removal of various amounts of material by chemical milling to permit uniform specimens at time of testing.

Amount Removed From Diameter, in.	YS, psi	UTS, psi	RA, %	El, % in 4D
Controls	182,000	192,750	30.0	10
0.005	180,750	191,000	31.9	10
0.014	181,500	191,500	34.9	10
0.040	180,500	190,500	31.9	10

Chemical milling of Ti-6Al-4V and Ti-8Al-1Mo-1V materials has also been investigated[25,26] for use in potential applications such as fuselage-skin tapering, sheet and plate sculpturing, and removal of excess forging stock. Results of tests on Ti-6Al-4V and Ti-8Al-1Mo-1V specimens (using both welded and unwelded materials) showed that chemical milling had no discernable influence on air fracture toughness or delayed fracture resistance of either of these materials. Constant-amplitude fatigue tests also showed no significant effect of chemical milling on the fatigue life of either of these alloys. Flight spectrum fatigue data

results on chemically milled materials were somewhat erratic, and further work was indicated as needed to arrive at more definitive results.

One source[29] indicated that, on the average, chemically milled specimens of the Ti-6Al-4V and Ti-5Al-2.5Sn alloys showed slightly better fatigue life than the as-received material. On the other hand, results by other workers[18] using fatigue tests (reversed-cantilever bending) on Ti-5Al-2.5Sn alloy sheet, indicated that chemical milling increased the hydrogen content of this alloy and reduced the fatigue strength slightly. Subsequent vacuum annealing of these parts reduced the hydrogen to a low level and increased fatigue strength significantly.

ELECTRIC-DISCHARGE MACHING

3-3.5.0 Introduction

Electric-discharge machining (EDM) has become well established in industry for fabrication or shaping of metal parts that cannot be readily produced by conventional methods because of the complex shapes involved or because of the toughness and hardness of materials. Up to very recently, die and tool making have constituted the major uses of the EDM process. Lately, production use of EDM has increased considerably in the electronics, aerospace, and other industries for machining complex shaped or fine-detailed parts, especially those made of hardened and tough metals. The use of EDM for machining the titanium alloys is at present rather limited. However, with efforts currently being made to improve EDM techniques for machining titanium alloys, the use of EDM on these alloy parts is expected to increase in the near future.

3-3.5.1 Process Principles

The EDM process can be described as the electrothermal shaping of parts by the controlled erosion or removal of metal by rapidly recurring spark discharges striking the workpiece surface. Although as yet there is no universally accepted theory regarding the exact mechanism of metal removal in EDM, it is generally agreed that erosion or metal removal is brought about by melting and possibly by some vaporization of the metal. Various theories are discussed in References (30) through (33).

A spark discharge will occur when the voltage difference across the gap between the tool electrode and the workpiece electrode becomes large enough to break down or ionize the dielectric fluid and cause it to act as an electrically conductive channel. For example[33], when the voltage between two electrodes separated by a gap of about 0.001 inch containing a dielectric fluid (such as a hydrocarbon oil) reaches about 70 volts, the dielectric becomes ionized and a discharge occurs. The electrons striking the workpiece change their kinetic energy into thermal energy or heat. This heat raises the surface temperature above the melting point, causing the formation of a liquid phase, and possibly some vapor phase and ions. The melted or vaporized metal particles are blasted away or ejected by the impact of the discharge. As the great flow of electrons occurs, the voltage between the electrodes drops to about 20 volts, which is low enough to stop electron flow. The ionized channel then collapses, the surrounding dielectric fluid takes its place, and the cycle is completed. The time to accomplish ionization is about 1 microsecond.

Since all of the molten metal produced by the discharge is not ejected, craters are formed on both the tool and workpiece. The size of the craters is determined by the amount of charge transferred, and normally the smaller craters are formed on the tool electrode. It is therefore desirable to transfer the charge in the shortest possible time to minimize thermal conduction into the body of the workpiece, while at the same time melting the maximum amount of metal. The transfer of a large amount of charge per discharge produces large craters and rough surface finishes, whereas a small amount of charge per discharge results in small craters and smoother surfaces.

Since each spark discharge removes a tiny bit of metal, the phenomenon described above can be used to machine or shape metal parts, because discharges take place between the closest points on the tool electrode and the workpiece. These spark discharges can be made to occur at frequencies of about 10,000 to 500,000 times per second. Thus, over a period of time, the rapidly occurring spark discharges will erode the workpiece in such a manner that the tool shape is reproduced in the workpiece with an accurately predicted overcut.

3-3.5.2 Machines and Equipment

3-3.5.2.0 Introduction

Figure 3-3.5.2.0-1 shows the main equipment components needed for an EDM operation. They include:

(1) A machine to hold the shaped tool(s) and workpiece(s) accurately positioned with respect to one another
(2) A power pack that supplies a readily controlled, high-frequency, pulsating direct current
(3) A servomechanism to accurately maintain the desired gap between the tool and the workpiece
(4) A system for pumping dielectric fluid to the machining zone, flushing away the eroded particles and removing the particles from the fluid.

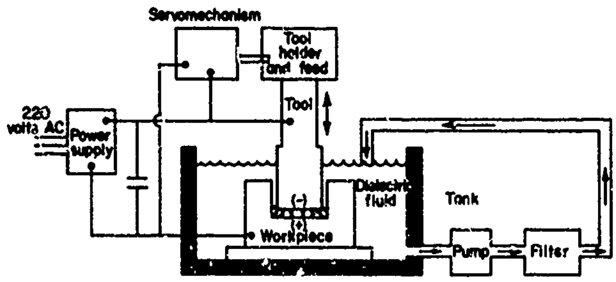

FIGURE 3-3.5.2.0-1. SCHEMATIC DIAGRAM OF A TYPICAL ELECTRIC-DISCHARGE MACHINING OPERATION

As shown in Figure 3-3.5.2.0-1, the tool and workpiece are set up for operation under the usual or standard polarity, i.e., the tool is cathodic or negative, while the workpiece is anodic or positive. With reverse polarity, the workpiece is the cathode and the tool is the anode. The choice of polarity to be used is governed mostly by the workpiece-tool material combination and also by other EDM operating conditions.

Figure 3-3.5.2.0-2 shows a typical general-purpose, heavy-duty EDM installation(34). The EDM machine is at center right, while the power pack and control console are at the left. The servomechanism is at the top center, above the tool holder; the workpiece is positioned on the worktable inside the dielectric tank. The dielectric circulating and filtering equipment are at the right-rear of the EDM machine.

3-3.5.2.1 Power Packs

Power packs come in a large number of sizes and use a variety of basic circuits to supply pulsating direct current to the EDM machines. Most EDM units now in use range from about 15 to 100 amperes in size; the recent trend is toward larger machines with capacities of 40 to 100 amperes and more. These larger units often have multiple current-supply features, so that they can supply current to several electrodes or to two or more separate EDM units. Although much of the EDM work is done at voltages in the range of about 30 to 100 volts, newer units are often being supplied with higher voltage outputs, e.g., 200 to 400 volts. Machining frequencies for EDM units range from about 10,000 to 300,000 cycles/sec and higher.

Each power pack will usually provide many combinations of currents, voltages, capacitances, and frequencies for use in achieving a wide range of metal-removal rates and surface finishes. Detailed information on commercially available power packs and EDM machines together with data on their ratings and capabilities can be obtained readily from EDM-equipment manufactures.

3-3.5.2.2 Gap-Controlling Servomechanism

Operating gaps between the tool and the workpiece generally range from about 0.0002 inch to about 0.015 inch. Generally, the smaller gaps are used for finishing-type work where smoother surfaces are desired. Conversely, EDM at larger gaps is used for roughing work carried out at higher metal-removal rates. The feed of the shaped tool electrode into the workpiece is controlled by the servomechanism, which acts to maintain a predetermined gap so that efficient machining can take place. The servomechanism receives a voltage signal from the machining gap; this voltage, which is gap dependent, is then compared with a specific reference voltage. The servomechanism, acting in response to the gap-voltage signal, will either advance or retract the tool so that machining will proceed at a specified voltage. The servomechanism will also retract the tool, if a shorted condition occurs, to allow the dielectric fluid to flush out the metallic debris causing the short, and then return the tool to the normal machining gap.

3-3.5.2.3 Dielectric Fluids

The dielectric fluid plays a very important role in the overall EDM operation. The dielectric fluid must act as an insulation between the tool and the workpiece until sufficient voltage is applied across the gap to make it break down and become a conductor for the spark discharge. The fluid must then quickly heal itself and again become an insulator so that electrical energy can be built up immediately to produce the next spark discharge. In addition, the dielectric acts as a coolant and also serves as the flushing medium for removal of metallic debris.

Although not indicated in Figure 3-3.5.2.0-1, the dielectric fluid is generally made to flow through small holes or openings in either the tool or the workpiece. Hole size and location are important in providing effective cooling and flushing of the spark-discharge zone. Dielectric pumping pressures generally range from about 10 to 100 psig, with the more normal range being about 10 to 40 psig. Vacuum or suction systems are sometimes employed to remove fluid and debris from the working zone. The dielectric fluid is filtered continuously in order to provide a steady flow of clean fluid to the EDM zone.

Hydrocarbon fluids possess good dielectric properties and are generally used for EDM. Frequently used hydrocarbons include: heavy transformer oils, paraffin oils, light oils, kerosenes and mixtures thereof. Silicone oils, polar compounds, deionized water, etc., have also been used for EDM operations.

Since dielectric fluids have significant effects on metal-removal rates, electrode wear, and other

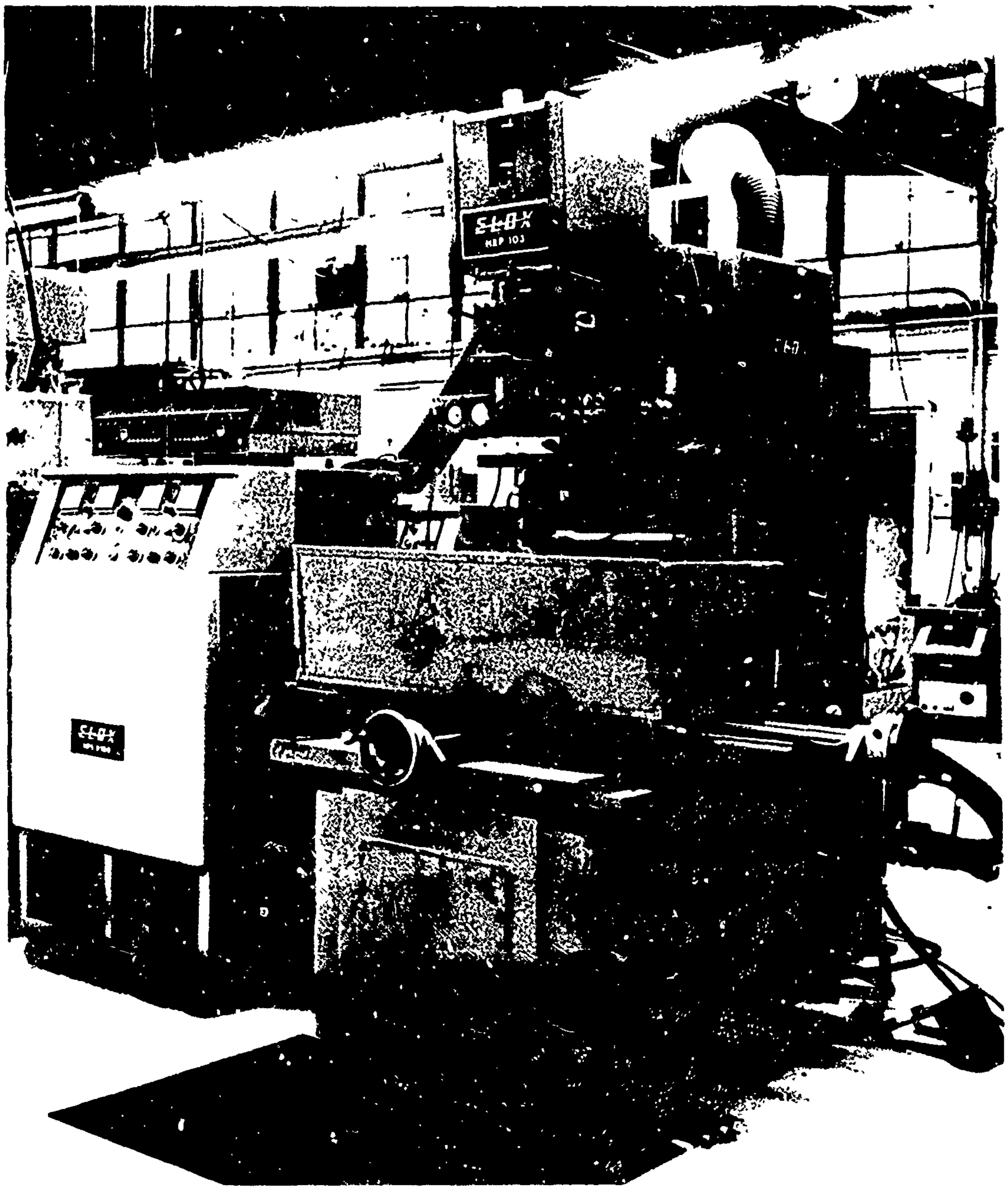

FIGURE 3-3.5.2.0-2. TYPICAL GENERAL-PURPOSE EDM INSTALLATION[34]

EDM operating characteristics, they should be carefully selected. Data and recommendations on dielectric fluids to use for various tool-workpiece combinations are usually available from EDM-equipment makers.

3-3.5.2.4 Electrodes

As indicated earlier, the tool electrode in EDM closely reproduces its own configuration in the workpiece. Thus, in a sense, it might be considered as comparable to a cutting tool in conventional machining. Some desirable characteristics of a good electrode material are:

(1) High metal-removal rate, i.e., from the workpiece
(2) Low wear, i.e., high metal removal from workpiece with low metal removal from electrode
(3) Ability to produce accurate parts with good surface finishes
(4) Ease and economy of machining or fabricating into tool configurations
(5) Low cost.

Selection of a particular electrode material is based on consideration of all of the above factors and how they apply to a particular EDM operation or

application. Electrode costs generally constitute a major or significant part of the overall EDM costs. Thus, electrode wear is especially important from the standpoint of EDM part accuracy and EDM costs.

Since wear is always present with EDM electrodes, efficient and relatively inexpensive methods of fabricating accurate tool shapes are desirable from an economy viewpoint. Electrodes are usually machined or ground by conventional machining procedures. Also, other methods such as forging, casting, electroforming, sintering of powdered-metal forms, etc., are often employed for electrode fabrication.

Among the more widely used electrode materials for general EDM operations are: carbon or graphite, brass, copper-tungsten, copper, zinc, tin, silver-tungsten, steel, and proprietary materials. Some performance data on various electrode materials used for EDM of titanium are presented below.

3-3.5.3 Operating and Performance Data

Relatively few specific data on operating conditions and overall performance characteristics for EDM of titanium alloys have been published. This lack of data may be associated to some extent with the fact it is relatively difficult to achieve good surface finishes by EDM on titanium alloys. Some specific EDM data and results on machining titanium-metal workpieces are presented below. Also presented are the generalized results of some aircraft-company evaluations of the use of the EDM for machining titanium-alloy parts.

Volumetric metal-removal rates for EDM of titanium workpieces with various electrode-tool metals are given in Table 3-3.5.3-1.[35] The higher metal-removal rates were obtained with cadmium, zinc, carbon, and copper electrodes. Data on the EDM operating conditions used in determining the metal-removal rates are given in the footnote of Table 3-3.5.3-1. Comparision data for machining iron and molybdenum, under similar EDM operating conditions used for titanium, are also given in this table.

Table 3-3.5.3-2, presents machining characteristics for EDM of titanium workpieces with various electrode tool metals.[36] The better metal-removal rates and workpiece/tool wear ratios were obtained with copper and zinc electrodes. Table 3-3.5.3-2 also indicates that the workpiece material/tool material combination greatly affects the stability of the machining operation and of the servomechanism system.

Electric-discharge machining of Ti-6Al-4V and Ti-8Al-1Mo-1V alloys was evaluated by Lockheed-California Company as part of one of their development programs.[25] The electric-discharge-machined titanium alloys exhibited a local layer of recast metal on their surfaces. Results of tension-tension fatigue tests ($R=0.1$, $K_t=2.7$) showed uniformly poor fatigue behavior. Microscopic examinations showed a thin layer of recast metal on the machined surface, which may have initiated early fracture. Accordingly, the use of EDM was not recommended as a final machining operation on titanium alloys because of its probable lowering of fatigue performance.

Based on studies conducted at the Norair Division of Northrop Corporation[37], results obtained in EDM machining of titanium alloys were generally not in keeping with aircraft-quality standards. EDM produced titanium-alloy parts with relatively rough surfaces, along with a heat-affected zone. Surface contamination from electrode burn-off was also reported. The use of EDM was suggested only for those parts or cuts where EDM was the only way of accomplishing the particular machining operation.

Results of some initial tests at Boeing[38] indicated a reduction in the fatigue life of electric-discharge machined Ti-8Al-1Mo-1V specimens. This work also indicated that considerable latitude exists in the selection of EDM operating conditions so as to produce smoother surface finishes and also to minimize the depth of the recast layer.

Figure 3-3.5.3-1 shows a Ti-5Al-2.5Sn alloy ring machined by EDM.[39] This ring forms a part of a three-stage compressor cage. Male and female graphite electrodes were used to produce the interior and exterior airfoil contours from previously mechanically machined bosses. The airfoil shapes were machined one at a time; the interior as well as the exterior shapes were machined in separate operations. Judicious choice of a particular grade of graphite-electrode material and hydrocarbon dielectric fluid, together with careful control of current, spark frequency, flushing, etc., were required to achieve good surface finishes on the part. The estimated wear ratio $\frac{\text{workpiece removal}}{\text{electrode removal}}$ for the above operation was about 2.5 to 1.

From discussions with EDM personnel in the field, it was learned that the more commonly used electrode materials for EDM of titanium alloys are brass, copper-tungsten, and graphite. Typical workpiece/electrode wear ratio were estimated as follows:

Brass	:	1:1
Cu-W	:	21/2-3:1
Graphite	:	2-3:1

Hydrocarbon dielectric fluids are generally used. Where contamination of the workpiece surface by

TABLE 3-3.5.3-1. VOLUMETRIC METAL-REMOVAL RATES FOR EDM OF TITANIUM AND OTHER METALS USING VARIOUS TOOL-ELECTRODE METALS[6, 35, a]

Tool-Electrode Metal / Workpiece Metal	C	Mg	Al	Ti	Fe	Cu	Zn	Cd
	Volumetric Metal Removal Rates, mm 37/min, for tool electrode metals indicated							
Titanium	5.25	3.24	1.96	0.27	0.67	3.5	25.4	29.1
Iron	13.38	1.62	2.87	1.45	0.33	10.9	4.10	11.5
Molybdenum	10.8	5.67	3.67	0.17	0.17	6.67	5.00	6.83

(a) EDM Test conditions were as follows:

Electrospark Machine	: Sparcatron Mark 3
Circuit Type	: RC relaxation
Circuit Parameters	: R = 27 ohms, C = 16 μF
Average Voltage	: 160 volts
Average Current	: 4 amp
Dielectric Fluid	: Commercial paraffin, continuously filtered
Workpieces	: Thin sheets, ranging from 0.005 to 0.065 in. thickness, of Johnson Matthey "Specpure" standardized substances or commerciallv pure metals.
Tool Electrodes	: Cylindrical rods, generally 3/16 in. in diameter of "Specpure" substances or commercial pure metals.
Duration of Test	: Time taken for electrode to drill hole through workpiece.

TABLE 3-3.5.3-2. EDM OF TITANIUM WITH VARIOUS TOOL-ELECTRODE MATERIALS

Workpiece Material	Tool Material	Machining Current, amp	Volumetric Metal Removal Rate, 0.001 in.^{3}/min	Volumetric Tool Wear Rate, 0.001 in.^{3}/min	Wear Ratio (Volume of Workpiece Removed to Volume of Tool Removed)	Machine Stability
Titanium	Zinc	14	3.8	9.2	0.41	Good
Titanium	Copper	10	2.8	0.36	7.8	Poor
Titanium	Magnesium	12	0.24	12.0	0.02	Good
Titanium	Aluminum	10	0.16	1.2	0.13	Fair
Titanium	Iron	12	0.12	0.7	0.17	Fair
Titanium	Titanium	2	0.03	0.06	0.50	Fair
Iron	Copper	12	0.95	0.50	1.9	Fair

carbon from the dielectric or graphite (carbon) electrodes may be a problem, use of distilled or deionized water, or some other non-carbon-containing dielectric might be considered.

3-3.5.4 Special Comments

In summation, it should be indicated that considerable care will be needed in deciding where it will be advantageous to use EDM for processing titanium aircraft parts. As indicated above, the recast layer produced by EDM may adversely affect fatigue performance of a part. Accordingly, for applications where this layer is undesirable, as for stressed parts subjected to vibratory loading, the surface layer should be removed. Thus, it is recommended that the EDM operation be followed by metal-removal treatments such as mechanical polishing, lapping, or boring, electropolishing, and chemical polishing. Shot peening or vapor blasting of the electropolished or chemically polished parts may also be employed to introduce compressive stresses to the processed parts to improve fatigue performance.

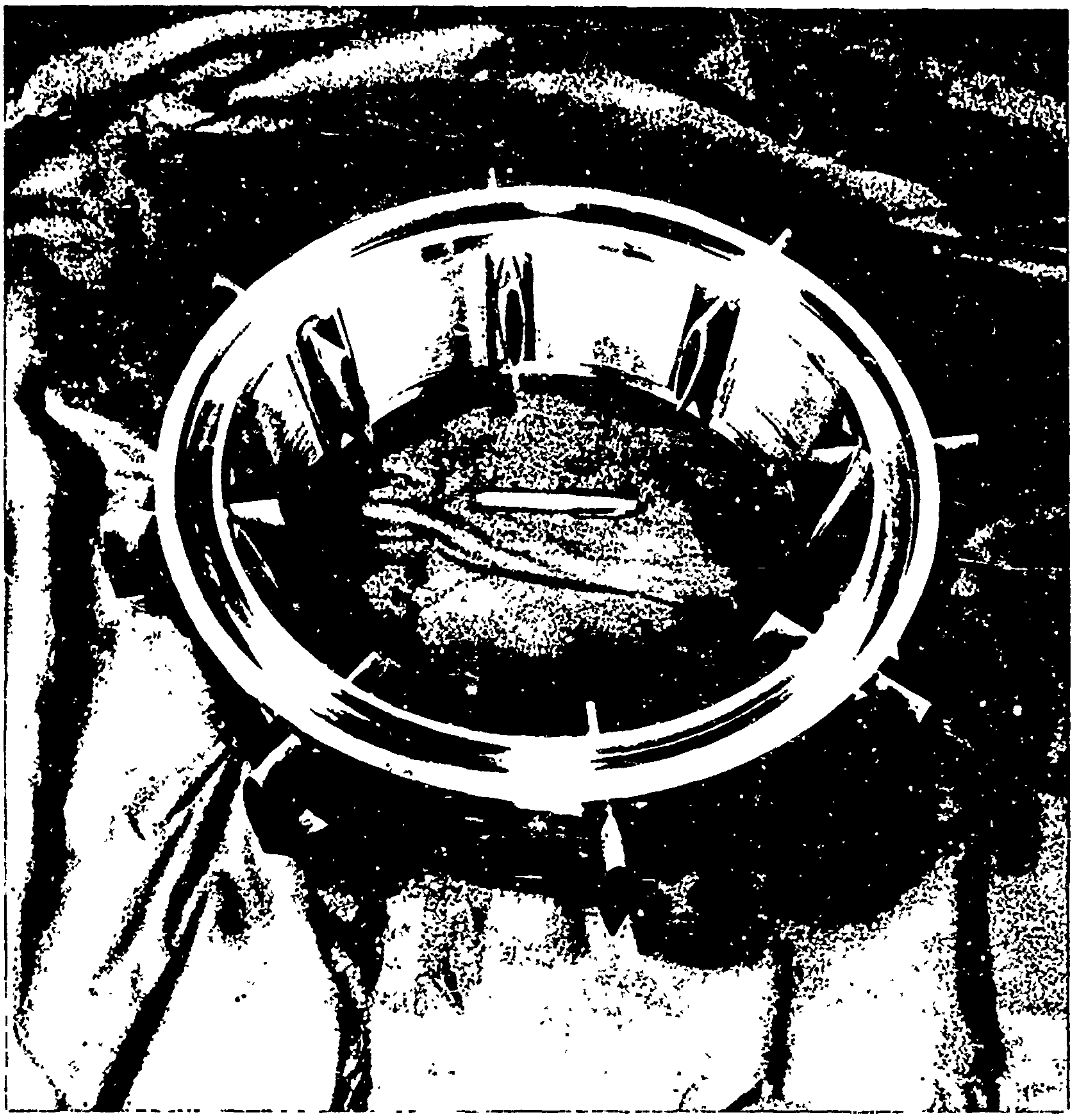

FIGURE 3-3.5.3-1. EDM-PROCESSED TITANIUM-ALLOY RING[39]

Continued research-and-development work on EDM operating conditions for machining titanium alloys is expected to produce parts with better surface finishes then those heretofore obtained. This should result in a greater utilization of the EDM process in the near future for machining intricately shaped titanium-alloy parts.

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3-10 General Forming Considerations

3-10.0 INTRODUCTION

Substantial improvements have been made in forming machines, dies, and manufacturing techniques during the last 5 years. Developments in vacuum forming, roll forming, and other processes have led to routine practices for forming titanium with a high degree of success.

Some companies prefer hot forming to improve formability and dimensional tolerances. Others use the cold-forming -- hot-sizing approach to accomplish the same result, namely parts with close tolerances and acceptable mechanical properties.

Cold forming is commonly employed in stretch forming skins and sections; sometimes the die is warmed to 300 F. For close tolerance work the stretch formed parts are generally hot sized after forming. Simple brake forming of straight sections also can be done at room temperature if adequate bend radii are designed into the tool. A variation in sheet orientation can be expected to affect the minimum bend radii which is obtainable at room temperature.

Ti-8Al-1Mo-1V can be cold formed to shallow contours using standard equipment. Bend radii must be larger than those for hot forming and the depth of the stretch flange smaller. Cold forming shapes in other alloys generally results in excessive springback, frequent interstage anneals, and requires more powerful equipment.

Stress relieving or hot sizing is usually required for cold-formed titanium parts to minimize residual stresses and to avoid delayed cracking or stress corrosion. Stress relieving is also necessary to restore compressive yield strength.

Hot-forming techniques are used on titanium and its alloys to increase formability, minimize springback, reduce variations in waviness between sheets, and produce maximum deformations with minimum interstage anneals. Severe forming operations must be performed in hot dies using preheated material. Dies designed for operation at temperatures as high as 1450 F for high-strength alloys are required.

Temperatures between 600 and 800 F are generally avoided for forming because most titanium alloys show a decrease in ductility in this temperature range. Forming at those temperatures may cause strain aging in alpha titanium alloys or precipitation hardening in certain alpha-beta titanium alloys. Usually it is desirable to use the lowest temperature which confers adequate formability. If maximum formability is desired, the highest temperature which does not degrade the properties of the part during service may be considered.

Some of the advantages and disadvantages of each approach are listed in Table 3-10.0-1.

TABLE 3-10.0-1 ADVANTAGES AND DISADVANTAGES OF HOT FORMING AND COLD FORMING - HOT SIZING APPROACHES

Hot Forming	Cold Forming-Hot Sizing
Advantages	
(1) Single Operation	(1) Forming can be accomplished on all available types of forming machines
(2) Lower forming pressures	(2) Reduced dwell time in cold forming press
(3) Material is at elevated temperature for shorter time	(3) Parts are stress relieved on sizing
	(4) Can use lower cost tooling materials in cold forming
Disadvantages	
(1) Requires temperature resistant tool materials	(1) Requires additional equipment (hot sizing presses)
(2) Tools must be adapted for heating	(2) Long dwell times in hot sizing press (30 min)
(3) Requires use of slow press with some dwell time (5 min)	(3) Long exposure times to elevated temperatures
(4) Limited to forming operations on equipment which can use heated tools	(4) Requires two sets of dies (one set heat resistant)

The decision as to which process approach to use normally depends on the types of forming equipment available and the part shapes to be made. If available press equipment can use heated dies, the hot forming approach is probably preferred.

3-10.1 FORMING TITANIUM

3-10.1.1 Forming Behavior

Titanium is more difficult to form than the more familiar steel and aluminum alloys. Close control of forming and allied fabrication processes and attention to details throughout processing are necessary. In spite of advances made in fabrication

techniques and control, successful forming of titanium still relies on a good deal of experience. Titanium alloys generally have less predictable forming characteristics than the available steel and aluminum alloys. Titanium, being a stronger material, requires higher forming pressures which must be closely controlled over a much smaller workability range. The spread between yield strength and ultimate strength, expressed as a percentage of the ultimate strength, is smaller. Other characteristics adversely affecting titanium formability include tendencies toward nonuniformities in sheet, notch sensitivity, moderate galling properties, low shrink capabilities, and potential embrittlement by overheating or by absorbed hydrogen, oxygen, or nitrogen during processing.

In spite of the problems, titanium is being formed successfully to the same tolerances as aircraft parts made from aluminum or stainless steel. The care required to obtain these results as well as the time required to form and the additional cost of elevated-temperature forming results in somewhat higher processing costs for titanium compared to stainless steels or aluminum. As greater forming experience is gained the metalworking costs for titanium are expected to decrease.

When formed at room temperature, commercially pure titanium and titanium alloys behave like cold-rolled stainless steel. For example, in stretch forming titanium seems to behave like full-hard stainless steel. Shapes that can be successfully press formed in 1/4-hard stainless steel usually can be press formed in commercially pure titanium; however, the latter may require hot sizing to produce severe contours. The formability of most titanium alloys at 1200 F is comparable to that of annealed stainless steel at room temperature. The optimum forming temperature depends on the alloy and the type of forming. For instance the commercially pure grades, being more ductile than the alloys, present fewer problems and can be fabricated to simple shapes at room temperature.

Springback in titanium, at room temperature, is not easily predictable. It tends to follow the yield strength/ultimate tensile strength ratio with higher ratios indicating greater amounts of springback. Springback in stretch forming of titanium alloys at room temperature has been reported to be as high as 20 to 30 percent of the bend angle. The greater amount of springback is not the major problem when cold forming titanium. The wide variations in yield strength among different heats magnified by a low modulus of elasticity can give a wide spread in springback angle, especially if the bend angle of the part is fixed by the forming tool.

All titanium alloys resist sudden movement; hence, stretching and pressing operations are usually recommended where a controlled rate of load application can be maintained. The slower the forming speed, the better the formability at room temperature. At elevated temperatures some titanium alloys, like Ti-6Al-4V, have better formabilities at higher forming speeds while others such as 13V-11Cr-3Al exhibit less ductility at higher forming speeds. From an economic viewpoint, faster speeds may be necessary, and even tolerable, if larger radii can be accommodated in the design. The formability of titanium is poor in operations characterized by shrink flanges such as found in rubber press forming. Consequently areas that require gathering of material should be minimized when designing parts.

Hot forming improves the forming characteristics of titanium mainly by increasing its ductility; major improvements normally occur above 1000 F for most titanium alloys. The yield strength normally starts to decrease at about the same temperature and results in lower forming pressures. At elevated temperatures the variations in yield strengths between heats and from shipment to shipment are smaller. Hence, parts formed at elevated temperatures exhibit greater contour uniformity.

3-10.1.2 Formability Ratings and Forming Limits

Materials can be arranged in the order of decreasing formability based on increasing yield strengths, yield strength/tensile strength ratios, and decreasing ductility. Formability ratings for various materials at varying temperatures in different processes have also been based on the material parameters and types of forming failures experienced. The types of failures and the controlling parameters for various forming processes are given in Table 3-10.1.2-1. When using conventional mechanical properties for determining the parameters, it should be remembered that only a small portion of a sheet is tested, and single values give no hint of uniformity. Table 3-10.1.2-2 shows the relative formability of some titanium alloys for six common aircraft forming operations.

Although it is possible to rate metals approximately in the order of their formabilities it is still impossible to predict precisely whether or not a desired shape can be formed. Hence, formability tests have been used to evaluate the forming characteristics and forming limits of titanium in various processes.

3-10.2 HANDLING AND CLEANING

3-10.2.0 Introduction

Blanks and parts must be handled with reasonable care to avoid nicks and scratches. These defects can lead to premature forming failures and possible part failure in service. Blanks or parts should be interleaved with paper between process steps and during storage.

Surface oxides or scale, if present, should be removed before forming. Such coatings can increase notch sensitivity during formings. Grease,

TABLE 3-10.1.2-1 TYPES OF FAILURES IN SHEET-FORMING PROCESSES AND MATERIAL PARAMETERS CONTROLLING DEFORMATION LIMITS(1)

The parameters can be determined in tensile and compressive tests.

Process	Cause of Failure: Splitting	Cause of Failure: Buckling	Ductility Parameter[a]	Buckling Parameters[b]
Brake forming	x		ϵ in 0.25 in.[c]	
Dimpling	x		ϵ in 2.0 in.[d]	
Beading				
Drop hammer	x		ϵ in 0.5 in.[c]	
Rubber press	x		(ϵ in 2.0 in.)(S_u)	
Sheet stretching	x		ϵ in 2.0 in.	
Joggling	x	x	ϵ in 0.02 in.	E_c/S_{cy}
..ner stretching	x	x	ϵ in 2.0 in.[e]	E_t/S_{ty}
Trapped rubber, stretching	x	x	ϵ in 2.0 in.[f]	E_t/S_{ty}
Trapped rubber, shrinking		x		E_c/S_{cy} and $1/S_{cy}$
Roll forming		x		E_t/S_{ty}(g) and E_c/S_{cy}(h)
Spinning		x		E_c/S_{cy} and E_t/S_u
Deep drawing		x		E_c/S_{cy} and S_{ty}/S_{cy}

(a) ϵ indicates natural or logarithmic strain; the dimensions indicate the distance over which it should be measured.
(b) E_c = modulus in compression; E_t = modulus in tension; S_{cy} = compressive yield strength; S_{ty} = tensile yield strength; S_u = ultimate tensile strength.
(c) Corrected for lateral contraction.
(d) For a standard 40-degree dimple.
(e) The correlation varies with sheet thickness.
(f) The correlation is independent of sheet thickness.
(g) For roll forming heel-in sections.
(h) For roll forming heel-out sections.

TABLE 3-10.1.2.2 RELATIVE FORMABILITY OF ANNEALED TITANIUM ALLOYS FOR SIX SHEET-FORMING OPERATIONS AT ROOM AND ELEVATED TEMPERATURES(2)

Brake Press (Minimum Bend Radius) at Room Temperature	Drop Hammer (Maximum Stretch) at 850 to 950 F	Hydropress (Trapped Rubber): Stretch (Maximum) at 600 to 700 F	Hydropress (Trapped Rubber): Shrink (Maximum) at 600 to 700 F	Joggle (Runout/Joggle-Depth Ratio): At Room Temperature	Joggle (Runout/Joggle-Depth Ratio): At 600 to 700 F	Stretch Wrap (Maximum) at Room Temperature	Skin Stretch (Maximum) at 850 to 950 F
13V-11Cr-3Al[a] (1.5T)	13V-11Cr-3Al[a] (16%)	13V-11Cr-3Al[a] (10%)	13V-11Cr-3Al[a] (6%)	13V-11Cr-3Al[a] (1.25)	13V-11Cr-3Al[a] (1)	8Mn (8%)	8Mn (18%)
8Mn (3T)	8Mn (16%)	8Mn (7.5%)	8Mn (5%)	8Mn (4)	8Mn (3)	5Al-2.5Sn (8%)	6Al-4V (17%)
5Al-2.5Sn (3.5T)	5Al-2.5Sn (13%)	6Al-4V (5%)	6Al-4V (4%)	5Al-2.5Sn (4)	6Al-4V (3)	13V-11Cr-3Al[a] (5.5%)	13V-11Cr-3Al[a] (13.5%)
7Al-2Cb-1Ta (4T)	6Al-4V (13%)	5Al-2.5Sn (<5%)	5Al-2.5Sn (3%)	6Al-4V (4.5)	5Al-2.5Sn (4.5)	6Al-4V (3.5%)	5Al-2.5Sn (12.5%)
4Al-3Mo-1V[a] (4.5T)							
2.5Al-16V[a] (4.5T)							
6Al-4V (4.5T)							
5Al-2.8Cr-1.2Fe (6.2T)							

Note: Alloys are listed in order of forming ease, the most formable alloy being at the top of the list. Numbers in parentheses following alloy designations are laboratory test values for the indexes of formability shown in parentheses at the top of each list. Laboratory index values shown should be relaxed at least 25 percent when designing for production.

(a) Solution-treated condition.
(b) Reference (7).

oil, and all solvents containing chlorides and residues of these solvents must be removed before any heating operation associated with forming, heat treating, or welding. Surface oxides must be removed after hot forming.

Conventional cleaning, etching, and descaling procedures can be used. They are usually covered by company specifications. When removing oxide from heat-treated or hot-formed parts, care should be taken to remove the oxygen-rich surface layer. Hence, parts requiring such treatments must be of sufficient gauge to allow for this metal removal treatment. Acid concentrations, temperatures, and etching rates should be carefully controlled to minimize local attack and dimensional changes.

Parts straightened or formed with tools made from lead, Kirksite, or low melting alloys should be cleaned in nitric acid.

3-10.2.1 Removal of Scale

Heavy gray and black scale formed on titanium at or above 1000 F can be removed either mechanically or chemically. Mechanical descaling methods include tumbling, vapor blasting, and fine grit blasting. Wire brushing and coarse grit blasting (No. 120 and coarser) are usually prohibited due to possible introduction of stress risers. Chemical descaling methods involve alkaline and acid baths with interstage and final rinses. The following chemical treatments have been used:

Process 1[3]

A. Blast scale with alumina
B. Swab surface with methyl ethyl ketone (M.E.K.)
C. Alkaline clean (5 minutes)
D. Hot-water-spray rinse
E. Acid clean (10 HNO_3 + 1 HF in water solution: 5 minutes)
F. Water rinse
G. Hot-water dip (deionized water)
H. Oven dry with forced air

Process 2[3]

A. Alkaline dip (15 minutes at 180 F)
B. Water rinse (hot spray for 3 minutes)
C. Scale-removal dip (a caustic-permanganate mixture like Turco 4338) (15 to 45 minutes at 180 F)
D. Hot-water-spray rinse (3 minutes)
E. HF-HNO_3 (1:10 mix) acid pickle (2 to 5 minutes)
F. Cold-water-spray rinse (3 minutes)
G. Hot-water dip (deionized water)
H. Dry with forced air

Process 3[3]

A. Descale with 47% HNO_3 (42° Be) + 6% Turco 4104 + water
B. Rinse thoroughly in hot-water spray
C. Dry with forced air

Small traces of scale remaining after descaling treatment can be removed by hand work using emery grit No. 180 or finer.

3-10.2.2 Removal of Mill Stencils and Grease

Heavy mill stencils and grease should be removed before forming operations. Clean surfaces favor more uniform deformation of the blanks. Heavy oils, greases, and fingerprints should be removed from the formed parts prior to pickling, stress relief, and annealing operations.

Methyl ethyl ketone (M.E.K.) is a widely used solvent for cleaning greasy or oily substances from titanium.

3-10.2.3 Removal of Oxides by Pickling

Thin oxides of titanium formed below 1000 F can be removed by pickling in acid baths approved for titanium. Blue oxide films formed between 700 and 800 F can be removed in 1 to 5 minutes; purple oxide films formed by more severe oxidation can be removed in 5 to 10 minutes. The colors can vary somewhat according to alloy and to previous mechanical and/or chemical treatments. The treatments are less severe than those recommended for scale.

Before pickling, all parts must be degreased with a nonchlorinated solvent (like M.E.K.) or alkaline cleaned to insure a uniform etch. Chemical cleaning involves immersing the part for one hour in a hot alkaline solution at 200 F, followed by thoroughly rinsing in water.

The pickling operation consists of immersing the part in a 20 percent nitric acid plus 2 percent hydrofluoric acid bath maintained at a temperature of 120 F just long enough to remove the oxide film. A cold 30 percent HNO_3 + 3 percent HF solution is just as effective. The acid is neutralized by immersing the part in a mild alkaline bath and rinsing by spraying thoroughly with cold deionized or demineralized water. The alkaline bath may not be needed if the part is rinsed thoroughly. The part is then dryed in a circulating air oven at 180-240 F or in an oil-free air blast.

Pickling after hot forming to remove 0.002 to 0.003 inch is sometimes advisable to remove any oxygen-rich surface layer. The final thickness, however, must not be reduced below the minimum gauge specified for the part.

3-10.3 SELECTED REFERENCES ON GENERAL FORMING CONSIDERATIONS

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(3) Personal communications, Boeing Airplane Company (October 31, 1964).

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(8) "Forming of Titanium and Titanium Alloys", TML Report No. 42, Volumes 1 and 2, Published by Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (May 18, 1956).

3-11 Preparation for Forming Processes

3-11.1 INCOMING INSPECTION

The success of forming and the reliability of the formed part depends on high-quality sheet material. This means that visual inspection for surface imperfections and gaging for flatness and tolerance discrepancies are usually necessary.

3-11.1.1 Visual Inspection

Incoming sheet should be inspected for proper identification, carrier damage, and proper surface condition. Titanium sheet and strip are usually marked, legibly and recurringly, to indicate the rolling direction. The markings also indicate gage, grade, heat number, test number, and customer specification number.

3-11.1.2 Laboratory Tests

The laboratory responsible for receiving inspection of materials may require a copy of the receiving report, the mill certificate of analysis, and additional samples 1 x 6 inches or 1 x 9 inches from each heat. The certified report should accompany each shipment from the mill. The sample of material that is sent to the laboratory should indicate the direction of rolling and be identified by the heat and the sheet number. The heat number is usually carried through final assembly of parts for identification only on materials that have demonstrated inconsistencies.

The samples are usually used for hardness, tensile, and bend tests. The results of the tests should be furnished to the receiving inspection group with recommendations for disposition of the material.

3-11.1.3 Gage and Flatness Inspections

The incoming sheets of material should be checked for flatness, thickness, and dimensional variations. Acceptance or rejection is normally determined by appropriate company specifications. The accepted material should be properly identified and placed in the stock room. Off-tolerance sheet may either be returned to the mill supplier or held for use on other parts. Often delays in delivery of material may necessitate the use of material of heavier gage than would be acceptable otherwise. Heavier gage material may be reduced in thickness by chemical milling or grinding.

3-11.2 HANDLING AND STORAGE OF TITANIUM

Handling of sheet materials does require special precautions. Sliding of titanium sheets against each other should be avoided because scratches may impair formability. Movement of material from one department to another should be done only when there is paper interleaving between the sheets or formed parts. When the sheets must slide across a table top, there should be a paper or plastic covering over the table.

Titanium sheets can be stored flat or on end. The sheets should always be interleaved with wrapping paper during storage. Covering the stacks helps to keep the material clean and free of grit. It is also advisable to store the material at room temperature for a short time before starting processing. This reduces the possibility of moisture condensing on the sheets and dirt pickup during handling. Storage should be in an orderly manner so that different alloys, gages, and sheet sizes are readily identifiable. The stacks should be arranged for ease of removing and resupply as the demand requires without damaging the sheets.

3-11.3 BLANK PREPARATION

3-11.3.0 Introduction

A variety of cutting processes may be used for the preparation of sheet-metal blanks from titanium. Some of the processes that have been used successfully for the preparation of titanium blanks are shearing, blanking, band sawing, slitting, and nibbling. Flame cutting or other thermal cutting processes are usually avoided and should not be used unless the heat-affected area is removed in a later operation.

3-11.3.1 Shearing

Sheet material up to 0.140-inch gage can be sheared to size without difficulty. Sheet with thicknesses between 0.140 and 0.187 inch have been sheared satisfactorily but require precautions. The sheet must be held firmly to prevent slipping during shearing. Shears used for mild steel may not have sufficient holding force to prevent slippage. The equipment should be checked for capabilities before being used for the production of titanium parts.[1]

Sheared edges, particularly in the heavier gages, may show some irregularities (0.01 to 0.02-inch deviation). This is generally the result of insufficient stiffness in the shear blade. Edge cracks may occur in some titanium sheet heavier than 0.080-inch gage. Shearing may be used in such cases if the cracks are removed by subsequent polishing or if they will be in the trim area of the part. When cracks occur in a critical section of the part, band sawing should be considered an an alternate cutting method.

Conventional power shears (square shears) with normal blade clearances and relief angles

appropriate for steel sheet can be used for shearing titanium. A power shear with a 3/16-inch mild-steel shear rating can cut up to 1/8-inch titanium sheet. Only sharp cutters should be used. Blades with nicks will contribute to edge cracking.

3-11.3.2 Blanking

Blanking is performed with a punch press on titanium sheet with gages up to 1/8-inch Small, irregular-shaped blanks up to 0.050 inch in thickness can be blanked from titanium sheet at room temperature, using dies made to tolerances of 0.004 inch. Sheet thicknesses from 0.064 to 0.125 inch can be successfully blanked at room temperature using dies with tolerances of 0.001 inch on part shape.[1]

Heavy die construction with suitable guide pins for proper alignment should be used for heavy sheet. Lack of stiffness in the tooling can contribute to die failure and to edge cracking of the blanks. The cutting edges must be kept sharp. Punching test for 0.25-inch diameter holes in annealed Ti-6Al-4V in thicknesses from 0.040 to 0.140 inch indicated that holes could be produced with a diameter tolerance of ±0.002 inch and a surface roughness of less than 50 RHR without delamination. Flat-point punches with 0.001-inch die clearance gave the best quality holes.[2]

3-11.3.3 Band Sawing

Band sawing prevents edge cracking in titanium sheet but results in larger burrs. The process is generally used for material of 0.125-inch gage or greater.[3]

High-quality machine tools of ample horsepower and rigidity give the best results when sawing titanium. The equipment should include automatic positive feeding, band tensioning, and a positive-flow coolant system. Only sharp, high-speed steel saw bands of appropriate pitch and width for the workpiece should be used. Consult the saw manufacturer for the proper blades and speeds for sawing titanium.

3-11.3.4 Slitting

Slitting is a suitable process for preparing long, narrow, thin blanks. It may be used for circle cutting as well as for irregular blank shapes provided the contour changes are not too sharp. The cut edge is generally smooth and free of shear cracks.[1]

Several types of equipment have been used successfully for slitting titanium. The conventional slitting equipment has shown promise as has the draw bench-type of equipment.

3-11.3.5 Nibbling

Nibbling can be used for producing irregular-shaped blanks. Short tool life and high maintenance costs are accepted as penalties for the convenience of producing a few pieces. The resulting cut edge is not smooth enough for most forming operations and should be conditioned by filing or belt grinding. The as-nibbled edge profile should not exceed the dimensions shown in Figure 3-11.3.5-1.

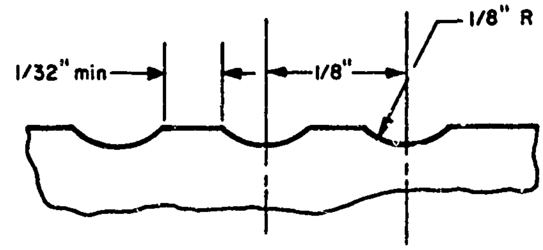

FIGURE 3-11.3.5-1. MAXIMUM PROFILE DIMENSIONS OF A NIBBLED EDGE

3-11.3.6 Edge Conditioning

Regardless of the cutting method, all blanks should be deburred. The edges of shrink and stretch flanges of titanium details must be polished prior to forming. The scratches resulting from the deburring or polishing operation should be parallel to the surface of the material. Cracks in the edge of sheared blanks are undesirable but may be acceptable if these are in an area that can be removed by trimming after forming.[1]

Sharp edges should be removed, and chamferred edges should be avoided. Scratches resulting from grinding or filing operations should be parallel and not across the edges of the blanks.

The edges of blanked holes and cutouts should be deburred on both sides. Polishing is generally required on blanks whose edges are to be stretched in subsequent forming operations. Draw filing and belt grinding are recommended for preparing edges of blanks up to 0.040 inch thick.

3-11.3.7 Sheet Layout Information

Layouts should be made in a manner that will use mill size sheets in the most practical and economical manner. The blanks should be marked with noncontaminating inks and pencils. Scribes or vibrating tools which damage the surface are unacceptable. The cutting sequence should be arranged so that the maximum number of parts can be cut from each sheet. The amount of work required for cutting irregularly shaped blanks can often be reduced by first shearing on a gross scale to obtain smaller sheets and then cutting the details. Although this method is generally wasteful of material it saves production time.[1]

Sufficient material should be left on blanks to permit removal of shear cracks and other stress raisers that might be present after blanking. Material up to 0.070 inch thick should have sufficient material allowance so that any evidence of surface defects can be removed. For heavier gages, it is common practice to allow an amount of edge material equal to the sheet thickness.

3-11.3.8 Surface Preparation

Scratches on the surface of a blank to be formed are detrimental to the formability of the part. Consequently, all necessary steps should be taken during blank preparation to reduce the possibility of scratches. All scratches both from processing and mill grinding which are coarser than the finish produced by emery grit No. 180 should be removed by surface sanding. This is normally a hand operation that can be very time consuming. Oil, grease, and other soluble matter should be removed before hot forming operations by using methyl ethyl ketone (M. E. K.) as a solvent on a wiping cloth. Some manufacturers resort to an acid etch to remove light scratches from the surface. Prior cleaning and degreasing is necessary to remove mill stenciling and other contaminants before etching. Uneven etching will result if this precaution is not taken.[4]

When titanium is to be heated in air for a long period of time, scale-inhibiting coatings are sometimes used to minimize surface contamination. Removal of this protective coating after the material has cooled to room temperature is necessary before the part is ready for assembly.

3-11.4 SELECTED REFERENCES ON PREPARATIO FOR FORMING PROCESSES

(1) Gerds, A. F., Strohecker, D. E., Byrer, T. G., and Boulger, F. W., "Deformation Processing of Titanium and Titanium Alloys", NASA Technical Memorandum NASA TM X-53438 Batteile Memorial Institute Contract No. DA-01-021-AMC-11651(2) (April 18, 1966).

(2) "Boeing Model 2707 Design Report, Part D, Materials and Processes", The Boeing Company, Report V2-B2707-8, Contract FA-55-66-5 (September 6, 1966).

(3) "Band Sawing of Titanium and Titanium Alloys", DMIC Memorandum No. 23, Defense Metals Information Center, Battelle Memorial Institute (July 1, 1959).

(4) "Belt Grinding of Titanium Sheet and Plate", DMIC Memorandum No. 11, Defense Metals Information Center, Battelle Memorial Institute (March 15, 1959).

(5) Personal communications, North American Aviation, Northrop-Norair, Douglas Aircraft Company, Lockheed Aircraft Corporation, Murdock Incorporated, Basic Industries Incorporated, and Harvey Aluminum Company (December 2, 1964).

3-12 Blank Heating Methods

3-12.0 INTRODUCTION

Titanium parts may be formed at room temperature or at elevated temperature. The choice between hot and cold forming techniques is based on the ability to make a part to the desired dimensions and mechanical properties. Most parts will require some thermal treatment during processing regardless of the forming technique used, so that heating methods are very important.

The time necessary to complete the hot-forming steps may limit the temperature used. At higher temperatures, the material properties will be degraded in shorter times. If a number of forming steps are required, it may be necessary to form at a lower temperature than that associated with maximum formability.

Temperatures can be determined with thermocouples embedded in the tools or with contact pyrometers. Temperature-sensitive crayons or paint should be used, but only on surfaces to be trimmed away, never on the part surfaces. Some companies prohibit the use of this type temperature indicator because of control difficulties.

Depending principally on severity, most hot-forming operations on titanium and its alloys fall within the temperature ranges of 400 to 600 F or 900 to 1000 F. Higher temperatures up to 1475 F may be required for the stronger alloys like Ti-8Al-1Mo-1V. Typical temperature for forming some titanium alloys by various processes are given in Table 3-12.0-1.

When titanium parts are formed at room temperature, a drop in compressive yield strength can be expected from the Bauschinger effect. As an example, it was found that as little as 2 percent plastic tensile strain results in a 40 percent loss in compression yield strength in annealed Ti-6Al-4V.[1] Almost complete recovery is obtained by thermal stress relief.

3-12.1 Heating of Blanks for Forming

3-12.1.0 Introduction

Blanks for forming may be heated by a variety of methods. Torch heating usually is not permitted, since local overheating and subsequent embrittlement of titanium can occur.

3-12.1.1 Furnace Heating

Portable electric furnaces with air atmospheres are often suitable for heating titanium blanks. Gas-heated furnaces are acceptable, provided the flame does not impinge on the part. Heating times, however, are usually longer for comparable blanks than those necessary for contact-heating, electrical-resistance-heating, or radiant-heating methods.

The transfer of large, heated blanks from furnaces can be awkward. Asbestos blankets are sometimes used to prevent undue heat loss during transfer from the furnace to the press. Chilling during transfer and contact with the dies normally makes furnace heating of thin-gage materials impractical.

The furnaces should be clean and completely free of contaminants. The hearth and refractories should be free of iron scale. A furnace previously used with an atmosphere other than air or inert gases should be purged for 4 hours before being used for titanium heating. This may be done by slightly opening the door of the furnace after it has been heated to the operating temperature.

Furnaces should be located adjacent to the forming equipment to minimize transfer time. The practice of heating to a higher temperature to compensate for the drop in temperature during transfer should be avoided. One piece should be heated at a time unless a fast forming cycle permits heating of several parts in a rotational inject and extract cycle. Each part should be formed as soon as it comes to temperature. Parts heated in air in the temperature range of 1100 to 1500 F may be surface coated to minimize oxidation.

Time at temperature should be held to an absolute minimum, consistent with complete penetration of heat into the blank. Titanium sheet heated in air above 1000 F should not accumulate excessive time at temperature. All heating and intermediate stress relief for multistage forming, creep forming, or final stress relief must be considered part of the cumulative time. This was explained in Section 1.

The temperature control of the furnace should be by automatic recording pyrometers or potentiometers. The furnace should maintain a temperature within 25 F of the intended temperature.

3-12.1.2 Resistance Heating

The relatively high electrical resistivity of titanium makes it suitable for internal-resistance heating. However, overheating of irregular sections and curved blanks is troublesome, and the transformer effect of adjacent steel tools can become a problem. Nevertheless, resistance heating has been successfully used for brake forming, drop-hammer forming, and matched-die forming.

TABLE 3-12.0-1 TEMPERATURES FOR SPECIFIC FORMING OPERATIONS[1,2,3]

Alloy	Forming Temperature, F: Mild Forming	Severe Forming(b)	Forming Method(a): A	B	C	D	E	F	G	H	I	J	Maximum Time at Temperature(b), minutes
Unalloyed	400-600	--	x	x	x	x	x	x	x				--
AMS	--	900-1000	x				x			x	x		120
4900 and 4901	--	1000-1300				x							--
Ti-8Mn	400-600	--		x			x	x	x				--
(AMS 4908)	--	900-1100	x		x		x	x	x	x	x		120
Ti-6Al-4V	400-600	--		x									--
(AMS 4928)	--	900-1000						x	x	x			30
	--	1000-1200			x						x		--
	--	1000-1450(c)	x			x	x	x					--
Ti-5Al-2.5Sn	400-600	--		x									--
		900-1000						x	x				--
		1000-1300(d)	x		x	x	x				x		90
Ti-8Al-1Mo-1V(e)	--	To 1500	x	x	x							x	--
	650	1200-1400	x										--
	--	1450					x	x			x		--

(a) Coded symbols: A = drop hammer; B = hydropress; C = brake; D = spin; E = draw; F = matched die; G = hydroform; H = finish die; I = creep form; J = sheet or form

(b) Temperatures should be held to a minimum to reduce scaling. Time at temperature is important, as titanium is embrittled by oxygen above 1000 F as a function of time and temperature. Generally, 2 hours is maximum for 1300 F; 20 minutes is maximum for 1600 F. These are accumulated times to include heating times for single or multistage forming, intermediate stress relief, and final stress relief.

(c) Temperatures up to 1600 F may be required for drop hammer, spinning, and matched forming.

(d) Temperatures up to 1600 F may be needed for spinning.

(e) Duplex annealed Ti-8Al-1Mo-1V can be hot formed in a broad temperature range without reduction in properties provided the material after forming is heat treated at 1450 F for 15 minutes, followed by quick cooling.

The temperature loss by a resistance-heated blank, before forming, is usually less than that experienced with portable furnace facilities. Blanks supported between dies during the heating period can be formed within seconds after the power is shut off. Consequently, it is relatively easy to control the forming temperature.

3-12.1.2.1 Clamping of Electrodes

Electrodes must be clamped securely and uniformly to the blank. Contacts should cover 100 percent of the ends of each blank for uniform distribution of current. Remotely operated clamps and automatic temperature controls are desirable for efficient heating. Safety usually requires the current to be cut off just before forming, although parts have been made with the current on.

3-12.1.2.2 Sources of Electrical Energy

A portable 440-volt, 75-kva, progressive spot-welding-type stepdown transformer is the minimum size that can supply appropriate amounts of electrical energy to heat small blanks.* Adjustable taps on the primary side provide secondary voltages from 2.5 to 35 volts and secondary currents from 400 to several thousand amperes. The size of the lead wires from transformer to electrodes is critical. Two 750,000-circular-mil wires have been used, and will carry approximately 1100 amps.

A 600-ampere d-c motor-generator set operating from a 60-ampere, 440-volt, 3-phase line also can be used to heat some of the smaller parts if other equipment is not available.

3-12.1.2.3 Power Requirements

The electrical power required to heat a titanium blank is a function of temperature, time, mass, surface area, and ambient temperature condition. Power-requirement tables can be prepared based on these variables.

3-12.1.3 Radiant Heating

Infrared heat sources (like T-3 quartz lamps) are used to heat blanks for hot-skin stretch forming of titanium. This technique is simple to use where one side of the blank is exposed to absorb radiation while being formed. It is difficult to control, however, when all parts of the blank are not the same distance from the heat source.

3-12.1.4 Hot-Die Heating

Hot-die heating of the blanks has advantages for simple operations such as brake forming. The tooling is placed in contact with the blank and held in that position until the blank is at the desired forming temperature. The forming force is then applied, and the part is formed.

* 100 square inches or less

Since this method heats only the part of the blank that is to be formed, it simplifies handling. The method can only be used for parts with simple contours where the area of the blank to be heated has good contact with the tool before forming.

3-12.2 DIE-HEATING METHODS

3-12.2.0 Introduction

It is desirable to use heated dies for forming titanium at temperature above 1000 F. For slow deformation processes, tools and platens are usually heated by electricity. Open flames cause poor working conditions and create problems in controlling temperatures.

Titanium cools rapidly when separated from its heat source and when the hot part is in contact with a tool which is at a lower temperature. Therefore, when it becomes necessary to form a part at high temperature (above 1000 F), it is desirable that the tool be at or near the same temperature as the part. For slow-forming processes, this means integrally heated or platen-heated tools operated at the forming temperature of the alloy being formed.

Die temperatures of 400 to 1500 F have been used when hot forming titanium. Temperatures depend on the titanium alloy, the shape of the part and the method of forming. Dies and platens are usually heated with electricity because of its flexibility, ease of control, and cleanliness.

3-12.2.1 Electrical Die Heating

Resistance-heated insulated dies that can be used on conventional equipment are the best approach to hot forming small detail parts. Figure 3-12.2.1-1 shows a typical die setup.

Large contoured skins can be formed on tools of cast ceramic material with resistance-heating wires embedded in the forming area.

Cartridge-type heaters are generally selected if tool dimensions are appropriate for the length of available elements. High-temperature-alloy sheaths should be specified for all high-temperature applications.

Strip heaters are also used by some companies.

No specific data on optimum spacing of heating elements are available. It is current practice to analyze each design to obtain uniform temperature over the working surface and a minimum of distortion throughout the tool. Higher density of cartridges is necessary around the perimeter of the tool to compensate for increased heat loss in this region.

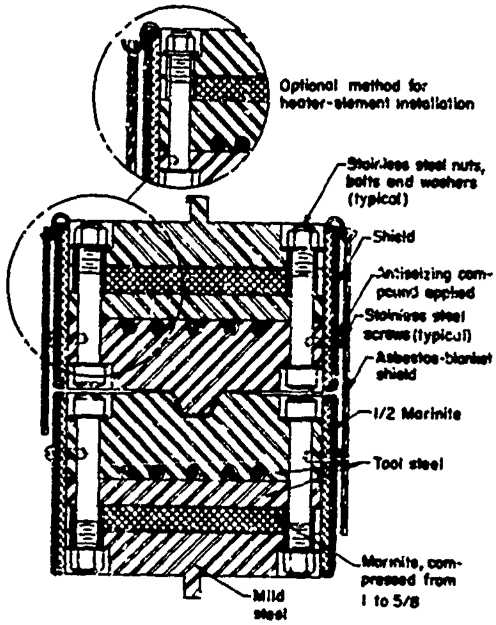

FIGURE 3-12.2.1-1. HEATING ARRANGEMENT FOR MATCHED DIES[1]

When the tool has a single heat control, temperature control is restricted to one thermocouple for indicating and recording. An excess temperature cutout actuated by a second thermocouple may be used to prevent overheating of the heater elements.

The primary temperature-control thermocouple should be located in contact with or within 1/8-inch distance of one of the elements.

The heating elements should be in contact with the die material at elevated temperatures to prevent overheating of elements. The elements should be mounted in machined grooves or holes drilled and reamed to the clearances specified by the manufacturer. However, slots may be more practical to fabricate. See cartridge-type heater manufacturers' recommendations for installation. Generous wiring space should be provided for expansion and contraction of the elements and to prevent chafing of the wires.

3-12.3 SELECTED REFERENCES ON BLANK HEATING METHODS

(1) Personal Communications, North American Aviation, Northrop-Norair, Douglas Aircraft Company, Lockheed Aircraft Corporation, Murdock Incorporated, Basic Industries Incorporated, and Harvey Aluminum Company, (December 2, 1964).

(2) Gerds, A. F., Strohecker, D. E., Byrer, T. G., and Boulger, F. W., "Deformation Processing of Titanium and Titanium Alloys", NASA Technical Memorandum NASA TM X-53438 (April 18, 1966), Battelle Memorial Institute, Contract No. DA-01-021-AMC-11651 (Z).

3-13 Lubricants for Forming

3-13.0 INTRODUCTION

Lubricants perform three main functions in titanium forming operations: (1) They minimize the energy of pressure required to overcome friction between the blank and the tooling, (2) they reduce the possibility of galling or seizing between the blank and the tooling, and (3) in hotworking, they control the rate of heat transfer between the hot blank and tooling. In general, friction is undesirable in metal-forming operations. Friction often increases tool forces and accentuates the difficulty of securing uniform movement of the material over the tooling. However in some operations, such as stretch forming, friction is necessary between the grips and the blank.

3-13.1 TYPES OF FORMING LUBRICANTS

Organic, nonchlorinated oils may be used in cold-forming operations. At elevated temperatures, boundary-type lubrication seems to be best. Consequently, it is common practice to add solids, such as graphite or molybdenum disulfide, to oils used for hot forming. Some of the various lubricants that have been used successfully for forming titanium alloys are listed in Table 3-13.1-1.

TABLE 3-13.1-1. FORMING LUBRICANTS[2,3,4]

Forming Operation	Forming Temperature	Lubricants Used
Stretch forming skins	Cold	Grease-oil combinations[a]
		Wax-type lubricant[b]
	Hot	Colloidal graphite[c]
Stretch forming sections	Cold	Wax-type lubricant[b] plus flake graphite(10:1 by volume)
Stretch forming extrusion	Hot	Molybdenum disulfide[d]
		Colloidal graphite[c]
Brake forming	Cold	Colloidal graphite[o]
Contour rolling sections	Cold	Heavy oil[f]
Roll forming	Cold	Heavy oil[f]
	Hot	Colloidal graphite[e]
Hot sizing	Hot	Colloidal graphite[e]
Drawforming (matched dies)	Hot	Colloidal graphite[e] plus alcohol - xylene
Hammer forming	Hot	Colloidal graphite[c,e]
Hydropress forming	Hot	Colloidal graphite[c]

(a) Like Stayput Lubricant 375.
(b) Like Johnson's Wax No. 150.
(c) Like Dag 41.
(d) Like Molykote
(e) Like Everlube T-50 Formkote
(f) Like SAE 60 oil

3-13.2 SELECTED REFERENCES FOR FORMING LUBRICANTS

(1) Adams, D. S. and Cattrell, W. M., "Development of Manufacturing Techniques and Processes for Titanium Alloys", AMC-TR No. 58-7-539, Ryan Aeronautical Company, San Diego, California, Contract AF 33(600)-31606 (July, 1958).

(2) Langlois, A. P., Murphy, J. F., and Green, E. E., "Titanium Development Program, Volume III", General Dynamics/Convair, San Diego, California, Report ASD TR 61-7-576, Final Technical Engineering Report for USAF, Contract AF 33(600)-34876 (May, 1961).

(3) Personal Communications, North American Aviation, Northrop-Norair, Douglas Aircraft Company, Lockheed Aircraft Corporation, Murdock Incorporated, Basic Industries Incorporated, and Harvey Aluminum Company (December 2, 1964).

(4) Personal Communications, Boeing Airplane Company (October 31, 1964).

3-14 Tooling Materials

3-14.0 INTRODUCTION

The choice of tooling materials depends on the forming operation, the forming temperature, and the number of parts to be produced.

3-14.1 TOOL MATERIALS FOR COLD FORMING[1,2,3]

Cold-forming operations, which stress the tooling in compression, can be conducted with tools made from epoxy-faced aluminum- or zinc-base alloys. The latter can be cast close to the desired dimensions and are easy and cheap to machine. Ceramic materials, cast iron, die steels, nickel-base alloys or stainless steels have been used successfully for hot-forming tools. Because machining is expensive, the cost of tool materials is usually a small part of tooling cost.

3-14.2 Tool Materials for Hot Forming

The ability of tooling to withstand wear and distortion at the forming temperature controls the number of parts that can be made on a set of dies. Good tooling is expensive. It is only justified when close tolerances or large production quantities are required. Frequently, design changes necessitate reworking or constructing new tooling. The selection of tooling materials is often a compromise based on expectations of tool performance and the number of parts to be produced before a design is changed. Sometimes it is more economical to use tooling that is cheaper to scrap and replace.

Table 3-14.2-1 lists some tool materials which have been considered satisfactory in various forming operations. It should be considered as a guide rather than as a recommendation. Boeing has recently contracted with Illinois Institute of Technology to determine the optimum alloys for tooling for the forming of titanium.[4]

TABLE 3-14.2-1. SELECTION OF TOOL MATERIALS[5,6,7,8,9]

Forming Operation	Type Forming	Tool Material
Stretch forming skins	Cold	Cast aluminum with epoxy face
	Hot	Cast ceramic (Glasrock)
Stretch forming sections	Cold	Kirksite form block
		Ampco Bronze No. 21 wiper die
	Hot	H-11, H-15 tool steel
		High-silicon cast iron
Stretch forming extrusions	Cold	Mild steel
	Cold	AISI 4130 steel
	Hot	AISI 4130 steel
	Hot	Type 310 stainless steel
Brake forming	Cold	AISI 4340 steel (36-40 R_C)
	Hot	H-11, H-13 tool steel
	Hot	Incoloy 802
Contour rolling sections	Col	02 tool steel
Yoder roll forming	Cold	02 tool steel
	Hot	H-11 tool steel
	Hot	H-13 tool steel
Hot sizing	Hot	Mild steel
	Hot	High-silicon cast iron
	Hot	High-silicon nodular cast iron
	Hot	H-13 tool steel
	Hot	Type 310 stainless steel
	Hot	RA 330 stainless steel
	Hot	Inconel X
	Hot	Hastelloy X
	Hot	Incoloy 802
Draw forming	Hot	High-silicon cast iron
	Hot	Incoloy 802
Hammer forming	Cold	Kirksite dies with stainless steel caps
	or	Lead punches with stainless steel caps
	Hot	High-silicon cast iron
		RA 330 stainless steel
		Inconel X
		Incoloy 802
Hydropress forming		Same as in hammer forming

3-14.3 SELECTED REFERENCES ON TOOLING MATERIALS

(1) Myers, D. E., "DOD High Strength Titanium Alloy Sheet Research Program", North American Aviation, Incorporated, Columbus, Ohio, BuWeps Contract NOas 57-785d Final Report (1963).

(2) Langlois, A. P., Murphy, J. F., and Green, E. E., "Titanium Development Program, Volume III", General Dynamics/Convair, San Diego, California, Report ASD TR 61-7-576, Final Technical Engineering Report, Contract AF 33(600)-34875 (May, 1961).

(3) Dohnal, F. and Cook, C. R., "Deep Drawing of Titanium Alloy Helmet Shell-6Al-4V", Thompson Ramo Wooldridge, Incorporated, Cleveland, Ohio, Final Report, USA Contract DA-19-129-QM-1430 (May 12, 1960).

(4) Plattner, C. M., "Boeing Pushes Titanium Airframe Effort", Aviation Week and Space Technology, 85 (26), pp 38-42, (December 26, 1966).

(5) Personal Communications, Boeing Airplane Company (October 31, 1964).

(6) Gerds, A. F., Strohecker, D. E., Byrer, T. G., Boulger, F. W., "Deformation Processing of Titanium and Titanium Alloys", NASA Technical Memorandum NASA TMX-53438, Battelle Memorial Institute, Columbus, Ohio, Contract No. DA-01-021-AMC-11651(Z), (April 18, 1966).

(7) Metals Handbook, 8th Edition, Volume I, American Society for Metals, Cleveland, Ohio (1961)

(8) Preliminary information reported by Grumman Aircraft Engineering Corporation, Bethpage, New York, on Contract AF 33(615)-5083.

(9) "Evaluation of New Titanium Sheet Alloys for Use in Airframe Construction on Volume V", North American Aviation, Incorporated, Los Angeles, California, AMC TR 60-7-561, Final Technical Engineering Report, Contract AF 33(600)-35597, (December 30, 1960).

3-15 Brake Forming

3-15.0 INTRODUCTION

Titanium and titanium alloys behave in brake forming like work-hardened stainless steels, except that the springback is considerably greater. The springback allowance is normally about 15° for cold forming. If the bend radii are sufficiently large, no unusual problems are encountered. When small bend radii cause cracking, it is necessary to use elevated-temperature forming procedures. Dwell times range around 30 seconds after the part is formed in heated dies.

Because titanium sheet is anisotropic, sections that are to be subsequently stretch formed should be bent parallel with the grain. Since maximum ductility occurs in the longitudinal direction, this practice permits more deformation during stretch forming.

3-15.1 EQUIPMENT SETUP AND TOOLING

Since brake forming is a rather standard operation, a number of good-quality tool steel dies are usually available. The punches are generally made to the desired bend radii, while the female die might be a "V" die or a channel die. The dimensions of a "V" that has been found to give satisfactory results is shown in Figure 3-15.1-1. Sometimes, to aid in forming, a hard-rubber insert is placed in the channel die. This helps reduce the possibility of scratching the surface of the formed parts, since the blank is only in contact with the punch and the rubber. The surface of the punch should be polished and free of nicks where it contacts the blank. Zinc-alloy dies can be used for producing limited quantities of brake-formed parts if the surface is covered so that the titanium does not touch the soft alloy. Stainless steel cover sheets are satisfactory for this purpose.

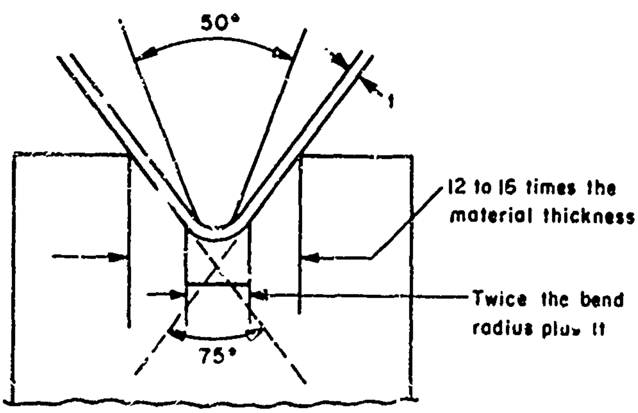

FIGURE 3-15.1-1. TYPICAL DIE SHAPE FOR BRAKE FORMING TITANIUM ALLOYS[1]

A protective coating should be applied to the surface of steel tooling used for hot forming in orde[r] to prevent scaling and pitting. A satisfactory coatin[g] can be built up by spraying a thin layer of Ni-Cr-B alloy on the surface of a grit-blasted tool and fusing the deposit at 1875 F. The coating is then polished to the desired smoothness. Stainless steel and high-temperature-alloy tooling have shown good results in other hot-forming processes and should be considered for brake forming.[2]

Punches can be heated to 1200 F by the use of integral cartridge heaters or by contact with heated copper back plates. "Transite" can be used to insulate the tooling from the platens of the press brake.[3,4]

3-15.2 BLANK HEATING PRIOR TO FORMING

The following temperatures have been reported[3,4] to be satisfactory for brake forming titanium and titanium alloys:

	Temperature, F	
Titanium Alloy	Blank	Punch and Die
Commercially pure	400-600	500
Ti-8Mr	900-1100	500
Ti-6Al-4V	1000-1200	500
Ti-5Al-2.5Sn	1000-1300	500
Ti-8Al-1Mo-1V	1100-1200	1150

The effect of temperature on brake formability of the titanium alloys is illustrated in Figure 3-15.2-1. The use of integrally heated brake punches and hot blanks is recommended for production operations. Heating blanks by contact with a hot punch and die is slow. To heat a titanium blank, 0.060 thick, to 900 to 1000 F with a die set heated to 1200 F requires about 4 minutes.

3-15.3 MINIMUM BEND RADII

The minimum bend radius decreases with increasing temperature for all titanium alloys. Table 3-15.3-1 shows the variation in minimum bend radii at various temperatures for the longitudinal and transverse directions of bending. The minimum bend radius also depends on the angle through which the bend is made, but normally bends that can be made at 90 degrees can be made at larger angles.

3-15.4 SPRINGBACK IN BRAKE FORMING

The springback depends on the ratio of bend radius to material thickness and the temperature of forming. For most titanium alloys, the greater the radius-to-thickness ratio and the lower the

forming temperature, the higher the springback angle. This is shown for Ti-6Al-4V alloy in Figure 3-15.4-1.

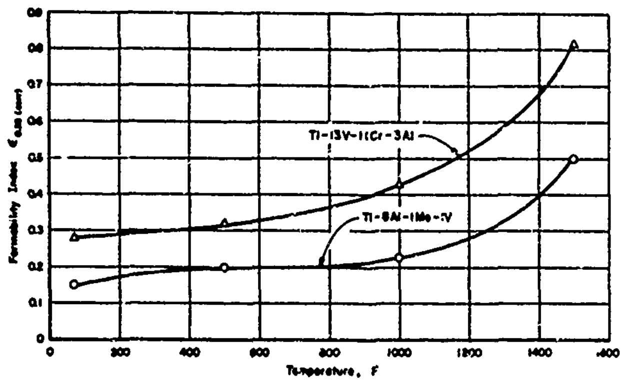

FIGURE 3-15.2-1. OPTIMUM FORMING-TEMPERATURE CURVES FOR BRAKE FORMING[5]

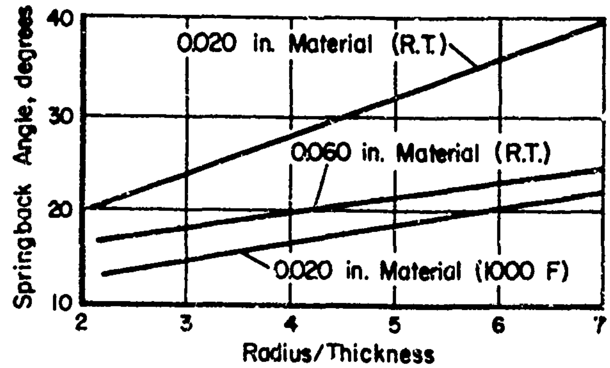

FIGURE 3-15.4-1. SPRINGBACK OF Ti-6Al-4V FOR VARIOUS BEND RADIUS-TO-THICKNESS RATIOS[6]

TABLE 3-15.3-1. MINIMUM-BEND TEST DATA (7)

		Minimum Bend Radius, T								
Temp, F	Bend Axis(a)	Ti-8Mn (RS 110A)	Ti-8Mn (MST 8Mn)	Ti-8Mn (C-110M)	Ti-5Al-2.5Sn (A-110AT)	Ti-6Al-4V (TMCA Ti-6Al-4V)	Ti-6Al-4V (MST 6Al-4V)	Ti-3Mn-1.5Al RS 110BX	Ti-3.25Mn-2.25Al RS 110BX (Mod.)	Ti-2.2Fe-2.1Cr-2Mo (TMCA Ti-140A)
70	L*	3-1/2	3-1/2	3	7	4-1/2	6	4	4	3
	T+	3-1/2	3	3	6	7	5	4	2-1/2	2-1/2
400	L	2-1/2	2-1/2	2-1/2	6	3-1/2	4	3	2-1/2	
	T	2-1/2	2-1/2	2-1/2	4-1/2	6-1/2	3-1/2	3	2	2
600	L	2	2-1/2	2-1/2	6	3-1/2	3-1/2	3	2	2
	T	2-1/2	2-1/2	2-1/2	4-1/2	5-1/2	3	2-1/2	1-1/2	2
800	L	2	2	2	5-1/2	5	3-1/2	2-1/2	1-1/2	1-1/2
	T	2-1/2	2	2	4	5	2-1/2	2	1-1/2	1-1/2
1000	L	1-1/2	1	1-1/2	5	2-1/2	3	2	1	1-1/2
	T	1-1/2	1-1/2	2	3-1/2	4	2-1/2	1-1/2	1	1
1200	L	--	--	--	3-1/2	2	2-1/2	--	--	--
	T	--	--	--	3	3	2	--	--	--
1400	L	--	--	--	2-1/2	1-1/2	1-1/2	--	--	--
	T	--	--	--	2-1/2	2	1-1/2	--	--	--
1500	L	--	--	--	1-1/2	1	1	--	--	--
	T	--	--	--	2	1	1	--	--	--

(a) L = bend axis perpendicular to rolling direction.
T = bend axis parallel to rolling direction.

3-15.5 SELECTED REFERENCES ON BRAKE FORMING

(1) Adams, D. S. and Catrell, W. M., "Development of Manufacturing Techniques and Process for Titanium Alloys", AMC-TR 58-7-539, Ryan Aeronautical Company, San Diego, California, Contract AF 33(-00)-31606 (July, 1958)

(2) Preliminary information reported by Grumman Aircraft Engineering Corporation, Bethpage, New York, under Contract No. AF 33(615)-5083.

(3) Personal communications, North American Aviation, Northrop-Norair, Douglas Aircraft Company, Lockheed Aircraft Corporation, Murdock Incorporated, Basic Industries Incorporated, and Harvey Aluminum Company (December 2, 1964).

(4) Personal communication, Boeing Airplane Company (October 31, 1964).

(5) Wood, W. W., et al., "Final Report on Advanced Theoretical Formability Manufacturing Technology", Volumes I and II, LTV Vought Aeronautics Division, Ling-Temco-Vought, Incorporated, Dallas, Texas, Contract AF 33(657)-10823 (January, 1965).

(6) "Boeing Model 2707 Airframe Design Report Part D, Materials and Processes", The Boeing Company, Report V2-B2707-8, Contract No. FA-SS-66-5 (September 6, 1966).

(7) Gerds, A. F., Strohecker, D. E., Byrer, T. G., and Boulger, F. W., "Deformation Processing of Titanium and Its Alloys", NASA Technical Memorandum NASA TM X-53438, Battelle Memorial Institute, Columbus, Ohio (April 18, 1966).

3-16 Stretch Forming

3-16.0 INTRODUCTION

Stretch forming is used to produce single-curved contours in sections and sheet, as well as certain compound curvatures in sheet.

The process starts by inserting an extrusion or brake-formed part of a sheet-metal blank in suitably shaped grips of the stretch-forming press. The blank is securely clamped and then stretched in the forming direction to produce 1 percent extrusion at the grips. Forming begins when the form block first contacts the blank and then deforms the part - either by pushing the form block against the part or by wrapping the part around the form block. Figure 3-16.0-1 illustrates the process for sheet. Tooling for stretch forming inboard and outboard angles is shown in Figure 3-16.0-2.

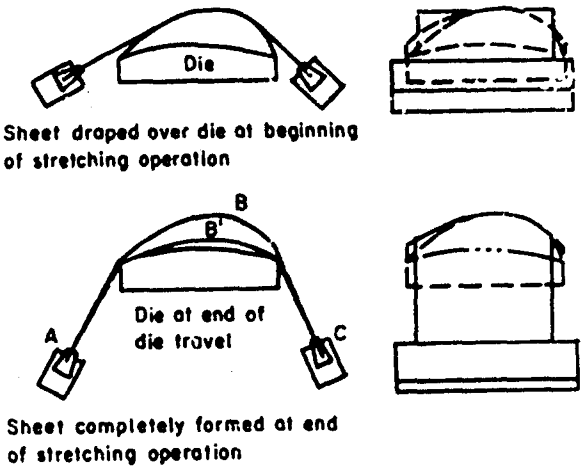

FIGURE 3-16.0-1. THE STRETCH-FORMING PROCESS[1]

Percent elongation = 100(ABC -AB'C) / (AB'C)

Skins are cold formed whenever possible to avoid the high cost of heated dies. The actual stretching operation requires excellent control of process variables and some handwork (tapping) by the operator.

When practical, sections to be contoured by stretching should also be cold formed to avoid loss of strength and excessive cross-sectional dimensional changes. When cold forming sections, a close control of hydraulic pressure and a slow wrapping action is required: about 0.75 to 1 degree per minute.[2]

It is sometimes preferable, or required (especially if insufficient forming power is available), to stretch wrap at elevated temperatures. The wrapping action must be done at slow speeds

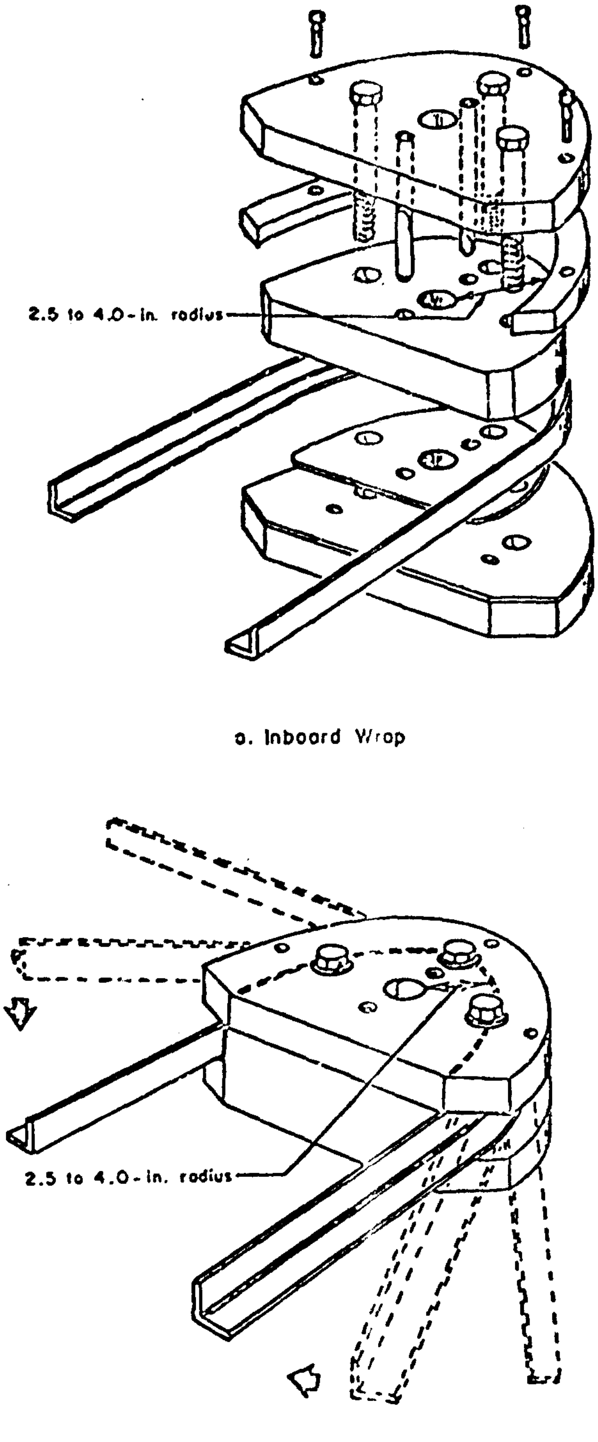

FIGURE 3-16.0-2. STRETCH-MACHINE (ANGLE SECTIONS) TOOLS[2]

to prevent local overheating or necking of the work piece as it makes progressive contact around the forming tool. After the wrap is completed, the stretching force may be reduced to a lower value

that is sufficient to maintain contact with the contoured hot-forming block. Contact should be maintained for about 15 minutes. Blanks may be heated by progressive contact with heated tools or can be preheated in a preforming position using radiant heat. Hot dies should be used in both cases throughout forming.

3-16.1 EQUIPMENT SETUP AND TOOLING

Stretch presses with a capacity of 150 to 600 tons are used for large skins or heavy sections. Small sections can be formed on simpler equipment of 25 to 35 tons capacity. Tooling can be characterized as room temperature or elevated temperature and as short term or long term. In general, the tooling used for stretch forming stainless steel can be used for cold forming titanium skins. The grips or hardened steel jaws of the press should have sharp, clean serrations, in good mechanical condition. The first four teeth near the jaw edges should be polished or ground down somewhat to prevent premature tearing of sheet blanks. High unit clamping pressures should be used to prevent slipping and tearing of sheet.

For short runs at room temperature, tools can be made from zinc-base alloys or from concrete faced with plastic. Tooling made from cast aluminum faced with a 3/4-inch layer of epoxy resin is suitable for larger production quantities. Heavy titanium sections can be stretch wrapped at room temperature on tools made from low-alloy steel such as A 4340.

A variety of materials have been used for stretch forming at elevated temperatures. Cast ceramic (Glasroc) tooling deserves consideration for forming temperatures above 1000 F. At lower temperatures, high-silicon cast iron, stainless steel, A 4130 steel, or H-11 tool steel are satisfactory.

3-16.2 MATERIAL PREPARATION

Sheets are sheared to size with excess metal provided to accomodate the grips and transition area between the grips and the tool. Sections are usually sawed to lengths needed for forming. In most cases, the excess metal is trimmed off after forming.

If a brake-formed blank is to be stretch wrapped, it is sometimes helpful to acid etch the strip before brake forming. A solution of 2 percent HF and 25 to 40 percent HNO_3 can be used. A surface removal of 0.002 inch from each side reduces notch sensitivity. The bend in the brake-formed blanks should be stress relieved within 24 hours after they are brake formed or before they are stretch formed.

3-16.3 BLANK HEATING PRIOR TO FORMING

Since stretch forming is a relatively slow process (taking about 5 minutes), it is impractical to preheat the blanks and transfer them to the machine. The blanks should be heated on the tooling and the tooling must be heated during the stretch-forming operation. The tooling can be integrally heated with cartridge-type units. For the Ti-8Al-1Mo-1V alloy, tooling temperatures should be maintained at 1000 to 1200 F. The blanks must be heated to about 1350 F. Resistance heating and radiant heating have been used for heating the blanks in stretch forming. Radiant heating has the advantage of applying the heat continuously during the forming, while resistance heating can only be applied while the blank is disconnected from the machine.

3-16.4 STRETCH-FORMING LIMITS

The formability of titanium alloys in stretch forming improves with increasing temperature. The formability index given in Figure 3-16.4-1 for several alloys indicates that temperatures above 1000 F are required before significant improvement is obtained in stretch formability.

3-16.4.1 Formed Sections and Extrusions Inboard

The formability limits for a formed section or extrusion to be stretch formed inboard, as shown in Figure 3-16.4.1-1, depends on the ductility and buckling limits of the material.

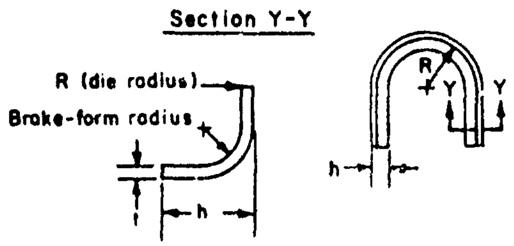

FIGURE 3-16.4.1-1. STRETCH-FORMED SECTION (INBOARD)(3,4,5)

The formability index for splitting limits depends on the conventional strain, ϵ, for a 2.0-inch gage length. The formability index for elastic buckling is a function of the ratio of tensile modulus to tensile yield (E_T/S_{ty}).

The index governing the optimum forming temperature will largely depend on the material thickness (t). For small values of (t), the ratio h/t becomes large, thereby placing this h/t value in the elastic buckling region, which is a function of (E_T/S_{ty}). For large values of (t), the conventional strain for a 2.0-inch gage length is the formability index used to determine the optimum forming temperature. The limit curves for general titanium alloys stretch formed inboard are shown in Figure 3-16.4.1-2. If it were possible to form 8-1-1 titanium alloy at 2000 F, considerable improvement in formability would be possible. The

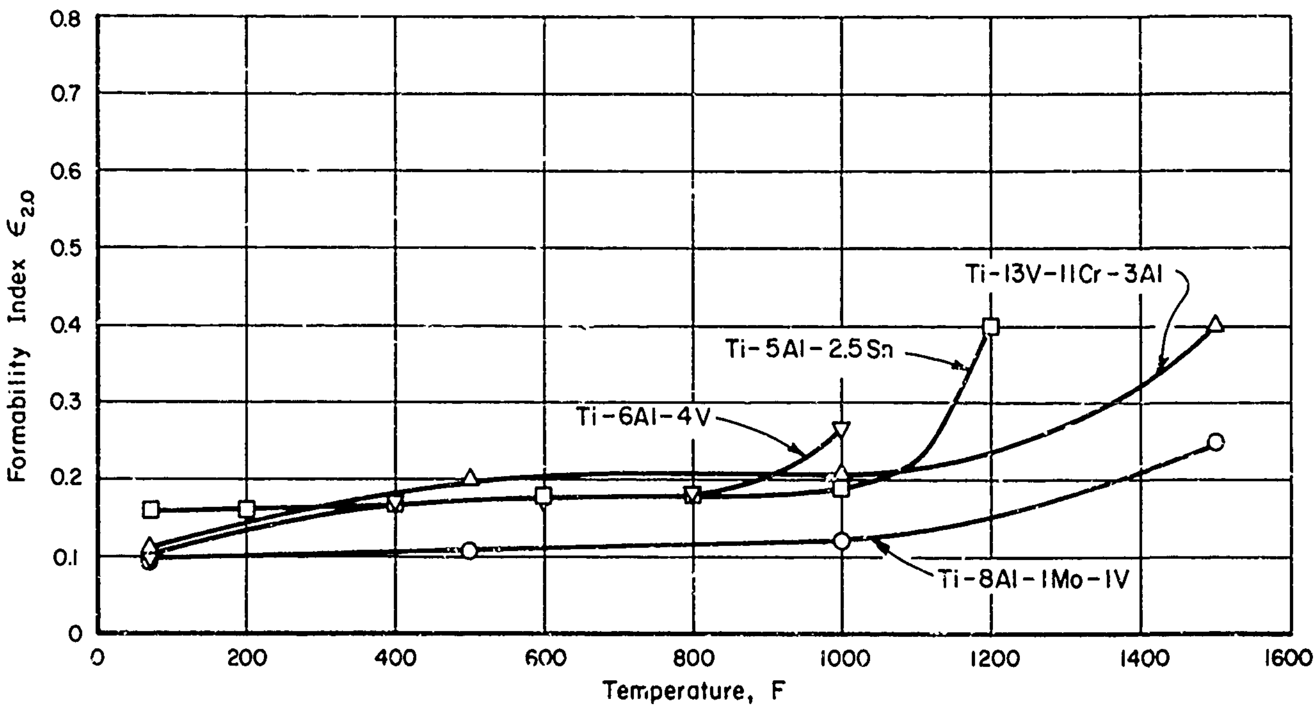

FIGURE 3-16.4-1 OPTIMUM FORMING TEMPERATURE CURVES FOR DIMPLING, LINEAR-STRETCH, SHEET-STRETCH, AND RUBBER-STRETCH FLANGE FORMING[3]

limit curves for stretch forming inboard hat sections is given in Figure 3-16.4.1-3.

3-16.4.2 Formed Outboard Sections

The formability limits for a formed section to be stretch formed, as shown in Figure 3-16.4.2-1, depend entirely on the splitting limits or the conventional strain.

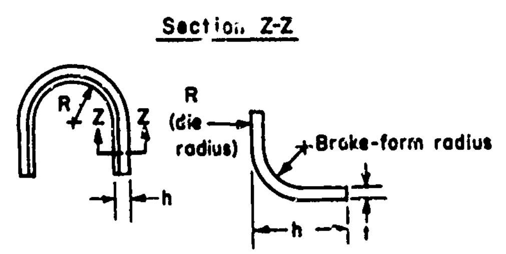

FIGURE 3-16.4.2-1 STRETCH-FORMED SECTION (OUTBOARD)[3,4,5]

The limit curves for various titanium alloys in stretch-formed outboard sections are given in Figure 3-16.4.2-2.

3-16.4.3 STRETCH FORMED SHEET

The forming limit curve for double contouring relatively large sheet metal parts is shown in Figure 3-16.4.3-1. The parameters that determine the curve are the longitudinal radius (R_L), transverse radius (R_T), longitudinal chord length (L), and transverse chord length (T).

Recent work indicates that thin titanium sheets can be creep stretch formed to close tolerances. A Haynes 25 form die heated to 1200 F was used to make double contour skins of Ti-6Al-4V and Ti-8Al-1Mo-1V alloy.[6]

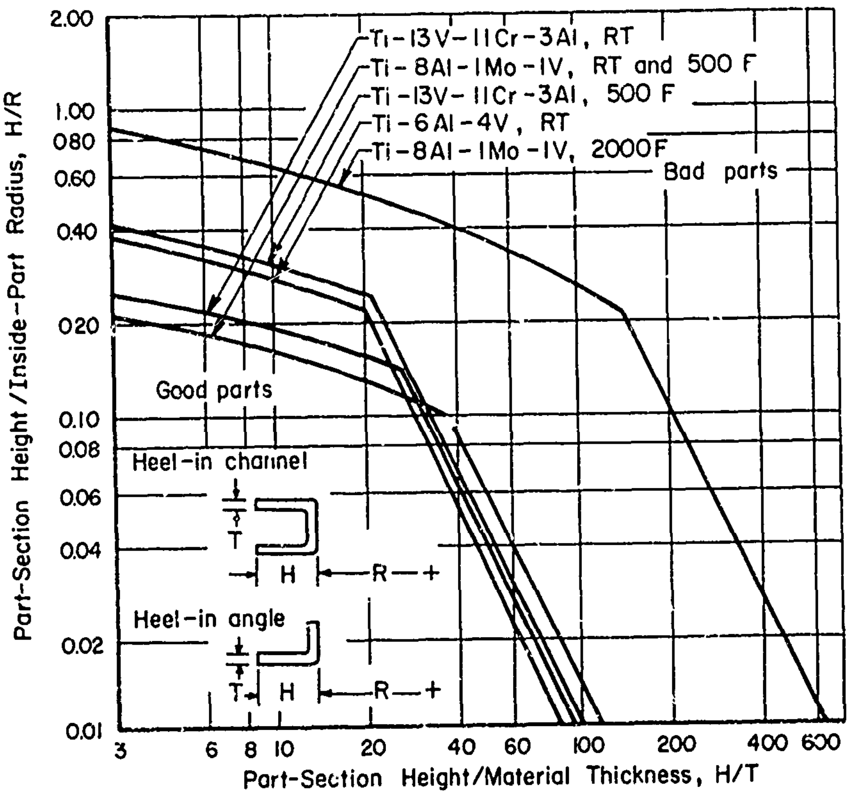

FIGURE 3-16.4.1-2. COMPOSITE LIMIT CURVES FOR TITANIUM LINEAR-STRETCH HEEL-IN (INBOARD) ANGLE AND CHANNEL SECTIONS AT VARIOUS TEMPERATURES[3]

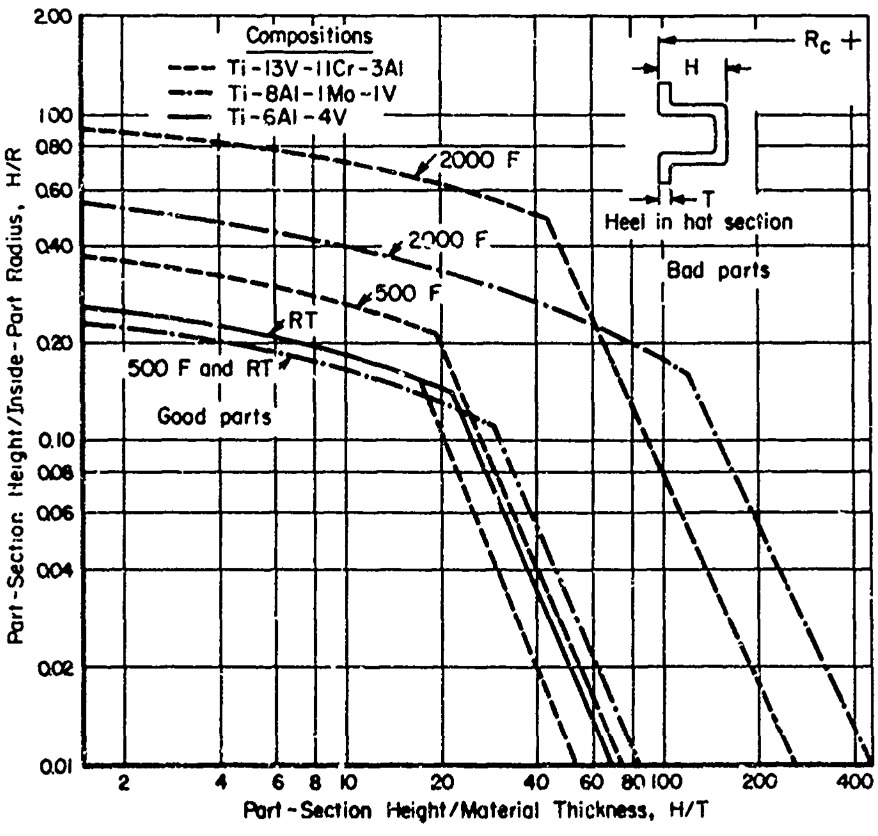

FIGURE 3-16.4.1-3. COMPOSITE OF OPTIM[illegible] TITANIUM LINEAR-STRETCH HEEL-IN HAT-SECTION-LIMIT CURVES IN THE ROOM-TEMPERATURE TO 2000 F RANGE[3]

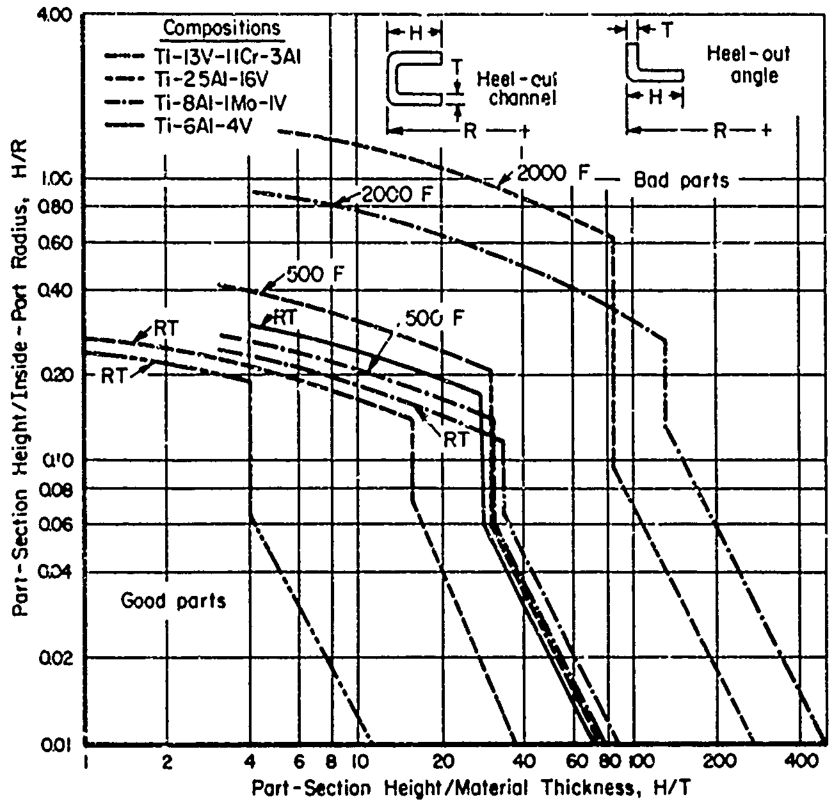

FIGURE 3-16.4.2-2. LINEAR-STRETCH HEEL-OUT-ANGLE-SECTION (OUTBOARD) TEST RESULTS AT ELEVATED TEMPERATURES(3)

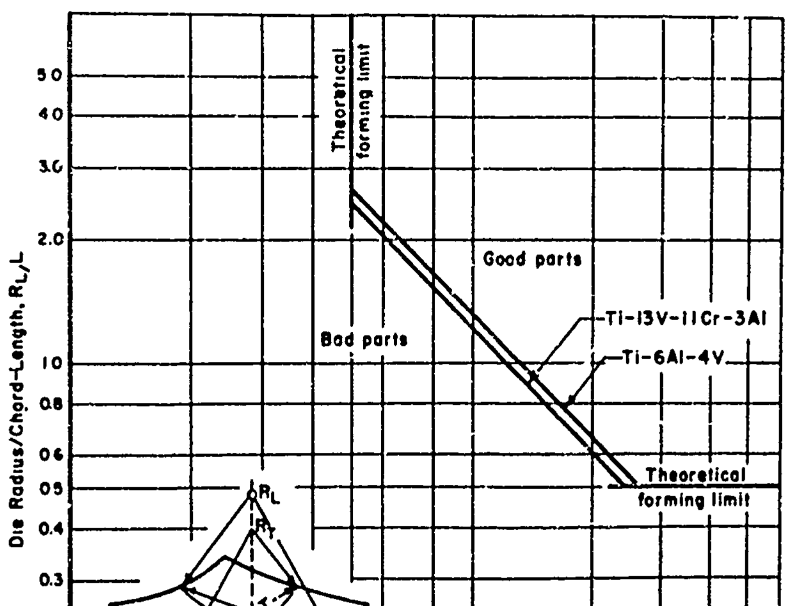

FIGURE 3-16.4.3-1. LIMITS FOR STRETCH FORMING TITANIUM SHEET(3)

The following tabulation[1,5] compares data on the stretch forming limits for different titanium alloys with those of stainless steel.

		Percent Stretch in Stretch Forming			
		Skin[b]			
		Cold			Sections[c]
Material	Condition[a]	Simple	Compound	Hot[d]	Cold
Unalloyed titanium	Annealed	(e)	(e)	20	20
Ti-8Mn	Annealed	(e)	(e)	20	15
Ti-5Al-2.5Sn	Annealed	(e)	(e)	20	8
Ti-8Al-1Mo-1V	Annealed	(e)	5[f]	(e)	(e)
Ti-6Al-4V	Annealed	9	4	20	6
Type 302 stainless steel	1/4-hard	--	--	--	15-20

(a) For titanium alloys only the annealed condition should be considered for stretch forming.
(b) For titanium-alloy skins the elongation perpendicular to the stretching direction should not exceed one-half the stretch.
(c) Titanium-alloy section can be stretch formed using up to 60 percent of the maximum allowable elongation of the material.
(d) Although cold-stretch forming is preferred, hot forming may be necessary if the press capacity is insufficient.
(e) Data, not available.
(f) Limited to 5 percent stretch. A majority of the SST skins planned for stretch forming fall within this limit.

3-16.5 STRETCH-FORMING CONDITIONS

A springback allowance is usually designed into tooling for stretch forming at room temperature. Nevertheless, variations among parts necessitate hot sizing about 10 percent of the time. Tooling for hot stretch forming is usually made to net dimensions.

The available stretch-forming presses can stretch wrap a 40 by 120-inch sheet of Ti-8Al-1Mo-1V alloy 0.090 inch thick. Sections and extrusions with cross-sectional areas up to 0.75 square inch and a length of 144 inches can be formed.

A slow and steady force should be applied during stretch forming. Sections are normally stretch formed at the rate of 0.75 to 1 degree per minute.

Various lubricants have been used for stretch forming titanium skins. At room temperature, brushed-on, extreme-pressure grease-oil lubricants, or disulfide-type lubricants can be used. Colloidal graphite and molybdenum have been used successfully on titanium sections for stretch forming at elevated temperatures.

3-16.6 POST FORMING OPERATIONS

When parts are stretch formed at room temperature, hot sizing is required to assure dimensional control. This step may also be required for hot-stretch-formed parts because limitations in the time the forming equipment can be tied up for dwell at temperature.

Stress relieving is required on all titanium parts that are stretch formed at room temperature and that are not subsequently hot sized. Check the heat treatment recommendations for the particular alloy under consideration.

Parts can be cleaned by Process 3 (see section on handling and cleaning) after hot sizing or stress relieving. They are then trimmed to net size and deburred. After a final cleaning with M.E.K., the parts are separated by wrapping paper or plastic sheets and placed in storage. Most companies handle the titanium parts with white gloves after forming to avoid contamination from fingerprints or other foreign matter.

3-16.7 SELECTED REFERENCES ON STRETCH FORMING

(1) Personal communications, Boeing Airplane Company (October 31, 1964).

(2) Gerds, A. F. Strohecker, D. E., Byrer, T. G., and Boulger, F. W., "Deformation Processing of Titanium and Its Alloys", NASA Technical Memorandum NASA TM-X-53438, Battelle Memorial Institute, Columbus, Ohio, Contract DA-01-021-AMC-11651(Z) (April 18, 1966).

(3) Wood, W. W., et at., "Final Report on Advanced Theoretical Formability Manufacturing Technology", Volume I and II, LTV Vought Aeronautics Division, Ling-Temco-Vought, Incorporated, Dallas, Texas, Contract AF 33 (657)-10823 (January, 1965).

(4) Wood, W. W., et al., "Volume I and Volume II Final Report on Sheet Metal Forming Technology", Aeronautics and Missiles Division, Chance Vought, Incorporated, Dallas, Texas, Contract AF 33(657)-7314 (July, 1963).

(5) Personal communications, North American Aviation, Northrop-Norair, Douglas Aircraft Company, Lockheed Aircraft Corporation, Murdock Incorporated, Basic Industries Incorporated, and Harvey Aluminum Company (December 2, 1964).

(6) Baxter, G. I., "Forming Thin Gage, Low Ductility Metals Magnesium. Titanium, Beryllium", General Dynamics/Convair, San Diego, California, R&D Report GDC-ERR-AN-873 (December, 1965).

3-17 Deep Drawing

3-17.0 INTRODUCTION

Deep drawing is a process for making deep-recessed parts by pulling a blank over a drawing radius into a die. A double-acting press is best adapted to the process because it permits controlling of hold-down pressures as well as of forming pressures. The process is suitable for high production rates on a wide range of part sizes which are limited only by the platen area of the press. Both mechaniical and hydraulically operated presses are used in deep drawing. The process has the disadvantage of being sensitive to tooling design and setup conditions. The correct conditions of pressure distribution, part lubrication, surface conditions, draw-ring radii, and part clearance must be maintained within very close limits for successful production. Variation in blank thickness is one of the most troublesome variables in the forming process.

Deep drawing is one of the most expensive forming operations because of the high cost of tooling and precision craftmanship required to establish a successful drawing operation. When elevated-temperature drawing is to be performed, the tooling problems are multiplied because of thermal distortion of the tooling. The process is ideally suited for forming large quantities of parts, but in general the tooling cost is not justifiable for making less than 100 parts.

Therefore, the use of this process for the fabrication of air-frame components has not matured, since neither the quantity nor the part shape justifies it. Similar shapes can be obtained by roll forming and welding.

3-17.1 EQUIPMENT SETUP AND TOOLING

A typical double-action, deep-drawing press is shown schematically in Figure 3-17.1-1. In operation, the blank is placed between the die draw ring and the pressure pad, and the desired hold-down pressure is applied. This pressure, which should be sufficient to resist buckling of the blank, is limited by the tensile strength of the material as it is pulled over the die radius. Too great a clearance between the punch and the die will permit the part to wrinkle, while too little clearance will cause ironing, increase the draw pressure, and possibly result in tensile failure of the part.

Since most titanium alloys have better drawing characteristics at slightly elevated temperatures than they have at room temperature, methods of applying heat to the blank during forming are of interest. A typical elevated-temperature setup was shown in Figure 3-12.2.1-1. The die set is insulated from the platens of the press by compressed "marinite". Cartridge-type heaters are integral with the die. Stainless steel hardware is used with the tooling to permit ease of assembly and disassembly after exposure to the elevated temperatures. The tooling shown in Figure 2-12.2.1-1 is for a single-acting press. Evaluation of Hastelloy X, Incoloy 802, and Meehanite HSV for draw tooling is under way.[2]

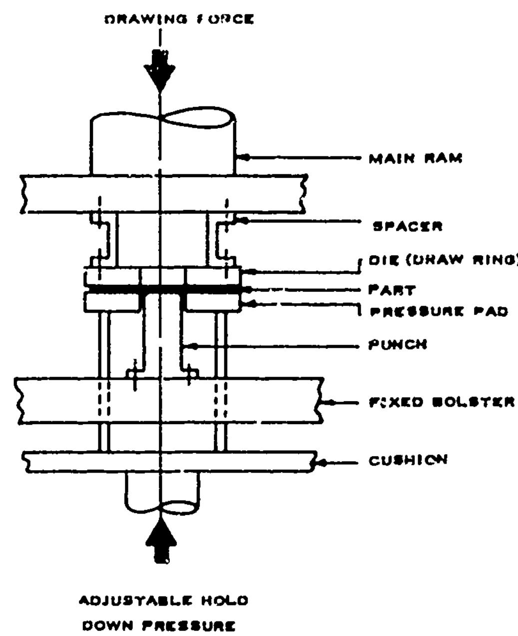

FIGURE 3-17.1-1. DOUBLE-ACTION DRAW DIE

3-17.2 MATERIAL PREPARATION

Titanium sheet-metal blanks for deep drawing should be prepared according to the practices and precautions described in previous sections.

A lubricant should be applied to the blank prior to forming. Some of the high-pressure, grease-oil-type lubricants can be used at room temperature, while colloidal graphite in an oil or grease carrier can be used for elevated-temperature forming.

Difficulties with buckling in the forming of thin sheets can be reduced by sandwiching the titanium between sheets of stainless steel or mild steel during forming.[3]

3-17.3 BLANK HEATING PRIOR TO FORMING

The blanks may be heated in an electric-resistance furnace placed next to the forming press, or by direct contact with heated dies. The former is a faster operation and works well with heated dies. The selection of a temperature for forming a particular alloy should be based on data indicating the effect of temperature on mechanical properties and on prior experience. Figure 3-17.3-1

shows the deep-drawing formability index of the titanium alloys. Both of the alloys shown should be drawn in the temperature range of 1200 to 1400 F.

The important dimensions are the cup depth H, the blank diameter D_B, and the inside cup diameter D_D. The material thickness and the draw radius are also important parameters but do not enter into the formability limits directly.

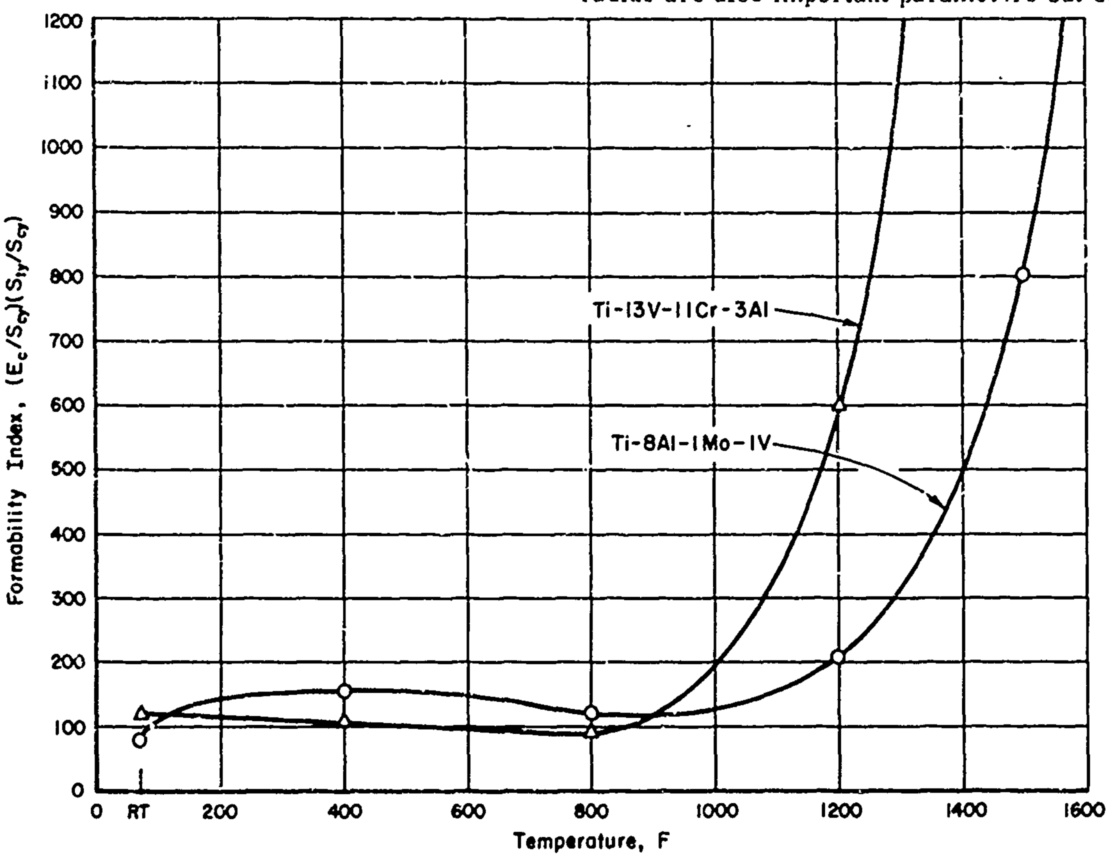

FIGURE 3-17.3-1. OPTIMUM FORMING TEMPERATURE CURVES FOR DEEP DRAWING[4]

3-17.4 DEEP-DRAWING FORMING LIMITS

The forming limit for deep drawing is established by buckling in the flange area and by fracture or splitting in the cup wall area. The limits have been found to be related to the ratio of compressive modulus and compressive yield strength for buckling and the tensile yield strength: compressive yield strength ratio for splitting. The geometric relationships in deep drawing are shown in Figure 3-17.4-1.

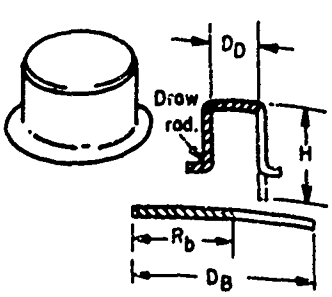

FIGURE 3-17.4-1. PART SHAPE AND PARAMETERS[4,5]

The formability limit curves for two titanium alloys at three different temperatures are shown in Figure 3-17.4-2. For both alloys considerable advantage can be obtained in drawability by increasing the temperature between 1200 and 1600 F. The ratios between die and blank diameter and cup depth to cup diameter are given in Table 3-17.4-1 for titanium alloys. The values are influenced by the ratio of cup diameter to material thickness. If the cup diameter increases at a constant material thickness, the blank to cup-diameter ratio decreases and the height-of-cup to cup-diameter ratio also decreases.

3-17.5 DEEP-DRAWING CONDITIONS

Sheets for deep drawing should be of uniform thickness to reduce the possibility of splitting failures. The presence of scale or dirt on the tooling should be avoided since it can change the coefficient of friction between the blank and the hold-down ring. This condition would cause uneven drawing of the blank from under the hold-down ring and result in a scrapped part.

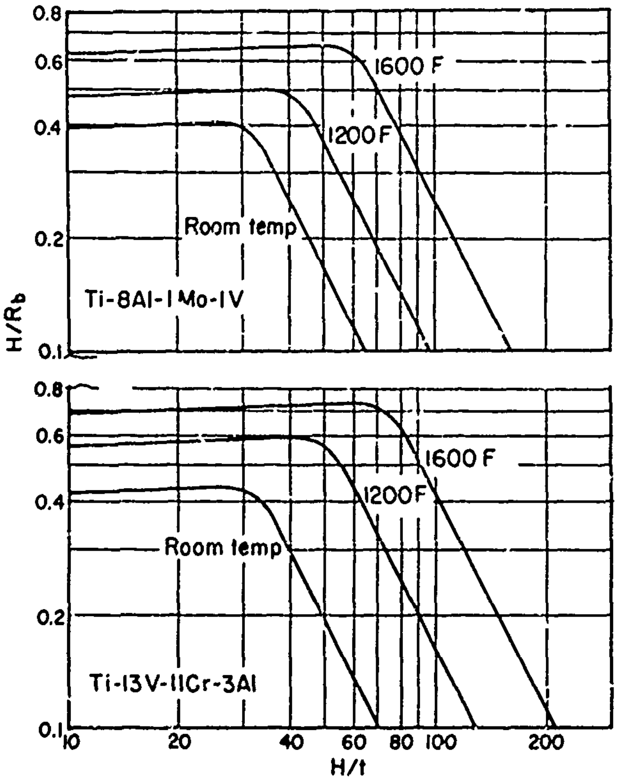

FIGURE 3-17.4-2. ANALYTICAL EXTENSION OF DEEP-DRAW-LIMIT CURVE FOR Ti-13V-11Cr-3Al AND Ti-8Al-1Mo-1V[4,5]

Since most deep-drawing operations involve considerable stretch and shrink of the material, elevated-temperature operations are preferred for titanium alloys. Tooling materials of Type 347 stainless steel or high-silicon Meehanite with integral heating cartridges can be used. The tooling is made to net dimensions since the forming takes place at elevated temperatures. Some draft in the tooling assists in removal of the formed parts from the tooling.

The tooling and the blank are heated to 1450 F for forming Ti-8Al-1Mo-1V alloy. In a typical operation, the part is formed at a slow speed of about 10 inches per minute and the pressure is held on the part for about 5 minutes after forming. The dwell time sizes the part and eliminates spring-back.[6]

3-17.6 SELECTED REFERENCES ON DEEP DRAWING

(1) Personal communications, Boeing Airplane Company (October 31, 1964).

(2) Preliminary information reported by Grumman Aircraft Engineering Corporation, Bethpage, New York, on Contract No. AF 33(615)-5083.

(3) Effenberger, L. J., Agricola, K. R., "Explosive Cold-Forming of Titanium Alloy Sheet and Foil", Martin Company, Denver, Colorado Paper presented at Sixth International Machine Tool & Design Conference, Manchester, England (September 13-15, 1965).

(4) Wood, W. W., et al; "Final Report on Advanced Theoretical Formability Manufacturing Technology", LTV Vought Aeronautics Division, Ling-Temco-Vought, Incorporated, Dallas, Texas, Contract AF 33(657)-10823 (January, 1965).

(5) Wood, W. W., et al; "Volume I and Volume II Final Report on Sheet Metal Forming Technology", Aeronautics and Missiles Division, Chance Vought Incorporated, Dallas, Texas, Contract AF 33(657)-7314 (July, 1963).

(6) Personal communications, North American Aviation, Northrop-Norair, Douglas Aircraft Company, Lockheed Aircraft Corporation, Murdock, Incorporated, Basic Industries, Incorporated, and Harvey Aluminum Company (December 2, 1964).

(7) Adams, D. S., and Catrell, W. M., "Development of Manufacturing Techniques and Process for Titanium Alloys", AMC-TR 58-7-539, Ryan Aeronautical Company, San Diego, California, Contract AF 33(600)-31606 (July, 1958).

(8) Myers, D. E., "DOD High Strength Titanium Alloy Sheet Research Program", North American Aviation, Incorporated, Columbus, Ohio, Navy BuWeps Contract NOas 57-785d Final Report (1963).

TABLE 3-17.4-1. DEEP DRAWING FLAT-BOTTOM CYLINDRICAL CUPS WITH MECHANICAL DIES AT ROOM TEMPERATURE[4,5]

		Die to Blank Diameter Ratios (D_B/D_D) and Cup-Depth Ratios (H/D_D) for Various D_D/T Ratios									
Material	Ratio	25	50	100	150	200	250	300	350	400	500
Ti-6Al-4V	D_B/D_D	1.7	1.7	1.7	1.5	1.4	1.4	1.3	1.3	1.2	1.2
	H/D_D	0.47	0.47	0.47	0.31	0.24	0.24	0.17	0.17	0.11	0.11
Ti-13V-11Cr-3Al	D_B/D_D	1.7	1.7	1.7	1.5	1.4	1.4	1.3	1.3	1.2	1.2
	H/D_D	0.47	0.47	0.47	0.31	0.24	0.24	0.17	0.17	0.11	0.11

(9) "Evaluation of New Titanium Sheet Alloys for Use in Airframe Construction Volume V", North American Aviation, Incorporated, Los Angeles, California, AMC TR 60-7-561, Final Technical Engineering Report, Contract AF 33(600)-33597 (December 30, 1960).

(10) Langlois, A. P., and Murphy, J. F., and Green, E. D., "Titanium Development Program, Volume III", General Dynamics/Convair, San Diego, California, Report ASD TR 61-7-576, Final Technical Engineering Report, Contract Contract AF 33(600)-34876 (May, 1961).

(11) Gunter, J. L., "Determination of Adaptability of Titanium Alloys-Volume Three-Processes and Parts Fabrication", Boeing Airplane Company, Seattle, Washington Final Report, AMC TR 58-7-574, Air Material Command, Contract AF 33(600)-33765 (December 1, 1958).

3-18 Trapped Rubber Forming

3-18.0 INTRODUCTION

Hydropress and trapped rubber forming are processes that utilize a contained fluid or a rubber mass as the female die. Since only a male die is required, the lead time and cost of tooling is reduced. The male tool is made to the desired contour and net dimensions. The springback is generally removed by subsequent hot sizing. The process is principally used for flanging and for shallow, recessed parts and has received wide acceptance in the airframe industries. One press can be used to make one large part or a number of smaller parts at one time. It can be used to make simple or complex shapes, including flanged sections with straight and contoured shapes and beaded panels.

Some of the limitations of the process, however, deter its use on titanium alloys. Insufficient pressure limits place a restriction on the maximum gage that can be formed. Poor shape definition in the higher strength materials as a result of limited pressure means subsequent steps such as hot sizing to obtain finished parts. Also, the process does not readily lend itself to elevated-temperature forming. Even with high-temperature rubbers, pad life is short at the temperatures above 1000 F required for good formability.

Some recent work indicates that titanium alloys can be worked at room temperature on a trapped-rubber impact machine with good results.[1]

3-18.1 EQUIPMENT SETUP AND TOOLING

The process may be conducted on either a single-action or a double-action press. A typical single-action-press setup is shown in Figure 3-18.1-1(a). The tool and blank rest on the bottom press platen, the trapped-rubber head is lowered over the tool, and then pressure is applied. This approach limits operating pressures because the rubber is never completely contained.

The use of a double-action press is shown in Figure 3-18.1-1(b). Here the blank is clamped against the rubber pad, and the rubber is completely contained. A punch from the bottom is then forced against the blank, and it is formed into the rubber pad. The advantages of this process are sometimes outweighed by the additional time and expense involved in tooling.

Forming pressures range up to about 3500 psi, or the limit which the tooling containing the trapped-rubber head will withstand. Consequently, the process is limited to forming alloys and gages of material that will deform below this pressure. A pneumatic-mechanical press equipped with a trapped-rubber head can develop pressures up to 20,000 psi.[1]

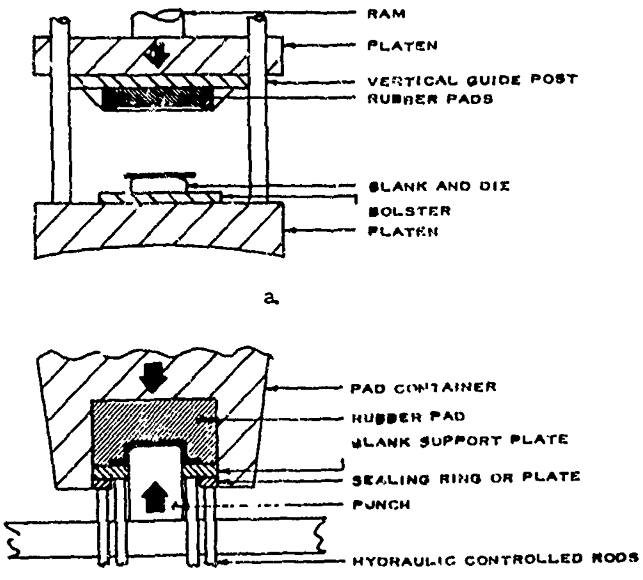

FIGURE 3-18.1-1 PRESSES FOR TRAPPED RUBBER FORMING

Trapped-rubber and hydroforming operations do not impose stringent requirements on tools. Mild steels are usually used, but other materials can be used if they do not contaminate the titanium parts. Lead- and zinc-alloy tools should not be in direct contact with titanium.

3-18.2 MATERIAL PREPARATION

Titanium sheet material for hydropress or trapped-rubber forming can be blanked by the methods described in Paragraphs 3-11.3. Generally, some tooling holes are required in the blank for positioning and holding until the press can close. Since only male tooling is used, it is necessary to lock the part in position on the die until it is completely formed.

3-18.3 TRAPPED-RUBBER FORMING LIMITS

The formability of materials on the hydropress are limited by the capacity of the press, plastic buckling, and splitting. The capacity of the press controls the range in size, strength, and thickness that can be formed. Within this range, however, additional limits will be set by buckling and splitting. Although both may occur in the same part, they are generally considered separately as shrink flanges and stretch flanges. The formability index for trapped-rubber forming of titanium shrink flanges at various temperatures is shown in Figure 3-18.3-1. Similar curves for trapped-rubber stretch flanges were shown in Figure 3-16.4-1. The forming limits for trapped-rubber stretch and shrink flanges at room temperature are

given for several alloys in Figures 3-18.3-2 and 3-18.3-3. The effect of rubber-pad pressure on minimum obtainable bend radii in trapped-rubber forming of 0.063-inch material is shown in Figure 3-18.3-4.

The limiting conditions for forming shrink and stretch flanges are determined, respectively, by buckling and by stretching. The limits for shrink flanges are related to the reciprocal of the compressive yield strength of the material for plastic buckling and to the ratio of compressive modulus to the compressive yield strength for the elastic buckling limit. The limits of stretch forming are related to the tensile ductility of the material for splitting limits and to the ratio of the tensile modulus to the tensile yield strength for buckling.

Some of the ratio limits that have been established for several titanium alloys at room temperature are given in Tables 3-18.3-1 and 3-18.3-2 for shrink and stretch flange forming on a hydropress with a pressure of 2000 psi. Comparing of the flange height limits on the hydropress with other metal forming processes shows why this process has limited application for forming strong materials such as the titanium alloys. Using a press that can provide higher pad pressure reduces the bend radii obtainable, as shown for two titanium alloys in Figure 3-18.3-4.

Springback can be very troublesome in hydropress or trapped-rubber forming. Some data obtained at various temperatures for some titanium alloys are shown in Table 3-18.3-1. Some of the temperatures investigated are exceptionally high and probably impractical for production operations. Increased pad pressure will decrease the springback on shrink flanges but has little effect on stretch flanges.[4]

Trapped-rubber forming is often used for forming beaded panels. The forming limits for beaded panels are determined by failures resulting from splitting or from buckling. Consequently success or failure depends on the ratio of the bead radius to the thickness of the material, R/T, or on the spacing of the beads, R/L. The limits for several titanium alloys made into beaded panels with a forming pressure of 3000 psi are given in Table 3-18.3-2. This table indicates that increasing the forming pressure increases the limiting R/T ratios and that raising the forming temperature permits closer beads in sheets of a particular gage.

3-18.4 TRAPPED-RUBBER FORMING CONDITIONS

Various types of rubber have been used in the machine heads with varying success. The rubber should have a Shore hardness between 70 and 90. Although some high-temperature rubbers have been developed for this operation, they are still limited to temperatures below 1000 F, where increased forming starts for many titanium alloys.

Most tooling is made to net dimensions, but undercutting the tools will sometimes reduce the amount of sizing required. An additional plate covering the blank area where no forming is to occur will sometimes improve part flatness.

A lubricant can be used on the blank or punch, although the advantage is very slight. Cleaning up the parts and tooling after each forming operation may involve more time than the benefit obtained from the lubricant.

3-18.5 POST-FORMING OPERATIONS

Since hydropress or trapped-rubber forming is normally carried out at room temperature, some type of thermal treatment is required within 24 hours after forming. Hot sizing will suffice; otherwise, the parts should be stress relieved.

Most parts are formed to the desired dimensions so that no trimming is necessary. If

TABLE 3-18.3-1 TRAPPED-RUBBER-FORMING TEST DATA[3]

Alloy	70 F Test, Springback, degrees		1100 F Test, Springback, degrees		1200 F Test, Springback, degrees		1500 F Test, Springback, degrees	
	Stretch	Shrink	Stretch	Shrink	Stretch	Shrink	Stretch	Shrink
Ti-3Mn-1.5Al	8	10	11	11	9	13	7	8
Ti-2Fe-2Cr-2Mo	12	13	11	11	9	8	0	1
Ti-8Mn	14	13	10	11	8	10	8	9
Ti-6Al-4V	11-15	12-13	13-14	13-14	12-13	11-12	6-8	4-7
Ti-6Al-4V	Fractured	Fractured	21-14	13-14	13-20	12-13	9-11	10-11
Ti-5Al-2.5Sn	14	14	18	14	14	14	12	12

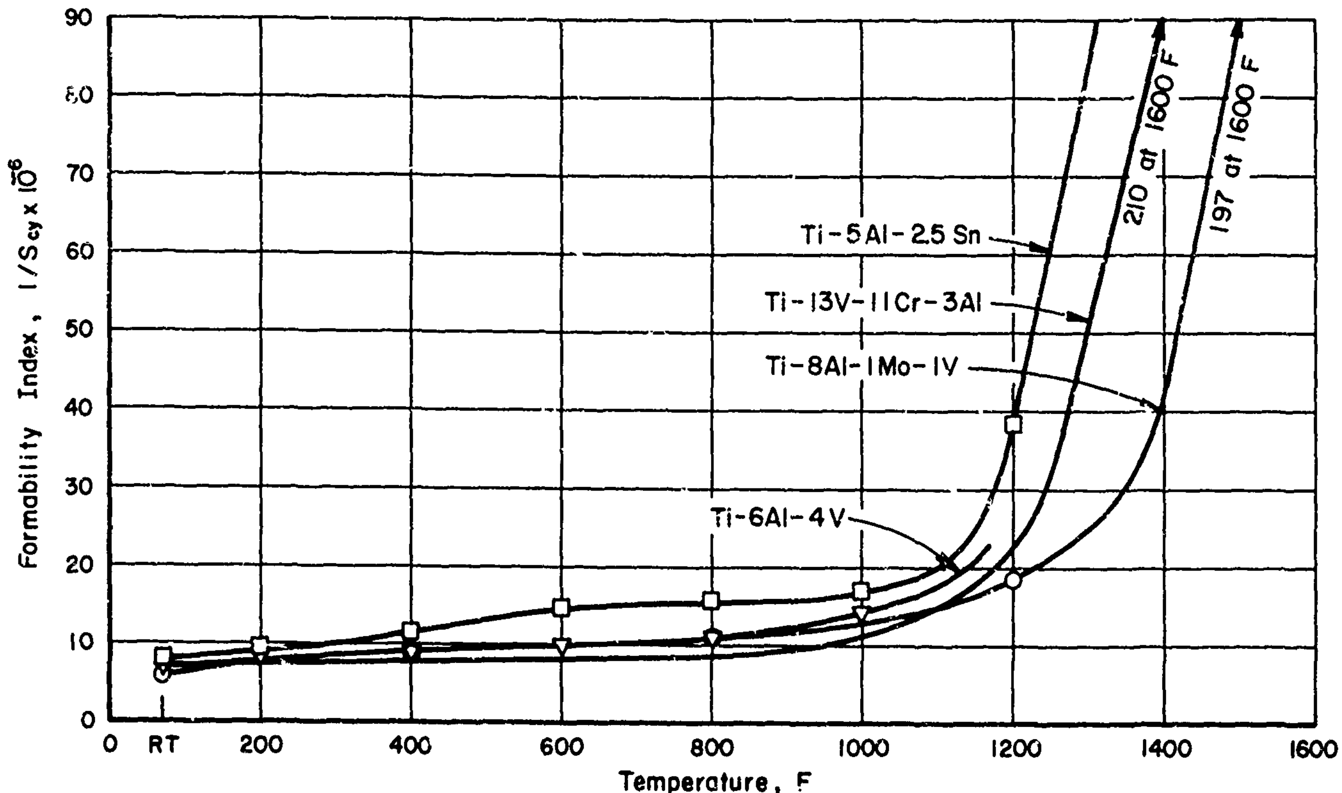

FIGURE 3-18.3-1 OPTIMUM FORMING CURVES FOR RUBBER-PRESS SHRINK FLANGES(2)

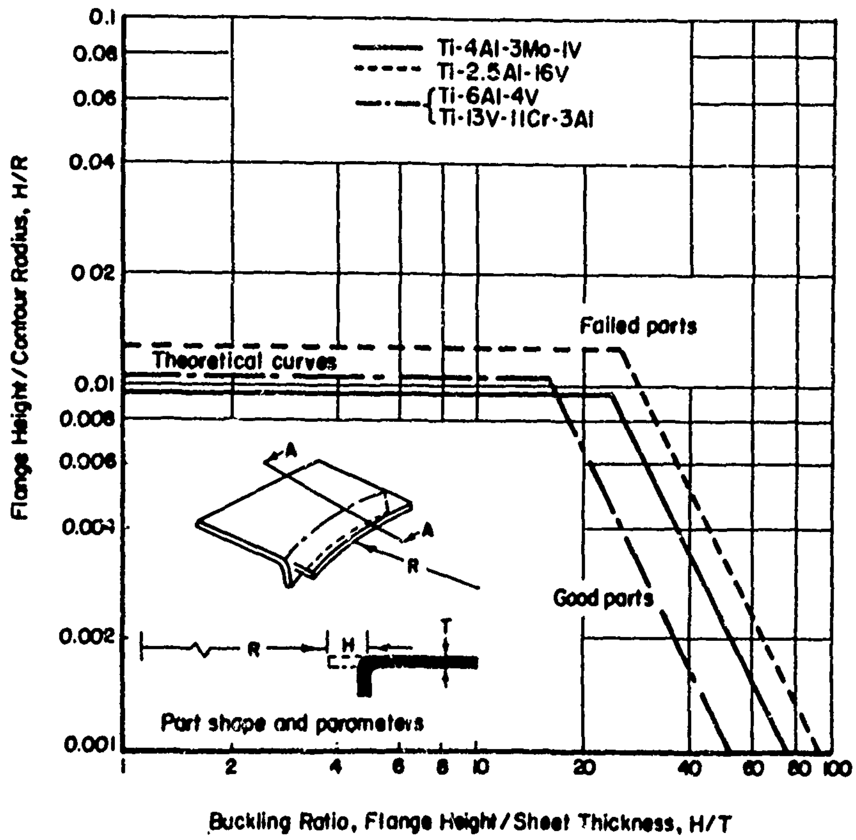

FIGURE 3-18.3-2 CALCULATED FORMABILITY LIMITS OF TITANIUM ALLOYS IN RUBBER-COMPRESSION-FLANGE FORMING AT ROOM TEMPERATURE IN COMPARISION WITH THE THEORETICAL CURVE(2)

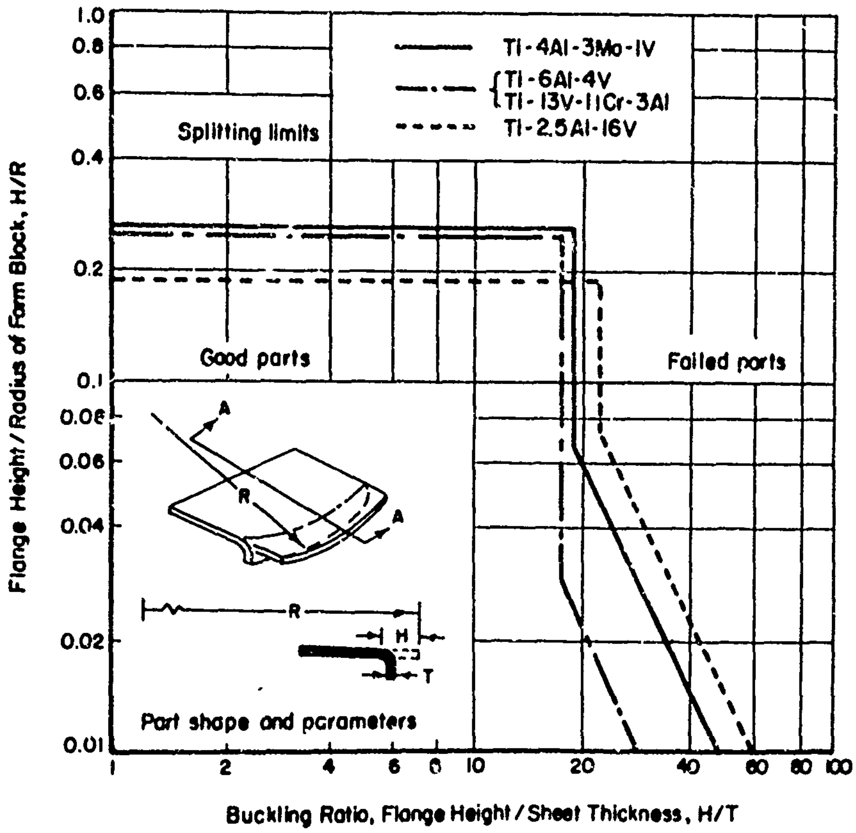

FIGURE 3-18.3-3 CALCULATED FORMABILITY LIMITS OF ANNEALED TITANIUM ALLOYS IN RUBBER-STRETCH-FLANGE FORMING AT ROOM TEMPERATURE[2]

TABLE 3-18.3-2 LIMITS[a] ON FORMING BEADED PANELS BY THE TRAPPED-RUBBER PROCESS WITH A PRESSURE OF 3000 PSI[3]

Material	Critical Ratio, L/T	Temp, F	Insufficient Pressure Limits, R/L	For R/T Ratios of 2	5	15	Splitting Limits, R/T Temp, F		For R/L Ratios of 0.01	0.03	0.06	0.10	0.15
Ti-8Al-1Mo-1V	147	RT	R/L	0.093	0.123	0.178	RT	R/T	52	47	44	---	---
			L/T	21.5	40.6	84.3		L/T	5200	1568	733		
Ti-8Al-1Mo-1V	121	1000	R/L	0.107	0.140	0.195	RT	R/T	52	47	44	---	---
			L/T	18.7	35.7	77.0		L/T	5200	1568	733	---	---
Ti-13V-11Cr-3Al	107	1000	R/L	0.125	0.165	0.230	500	R/T	60	54	50	---	---
			L/T	16.0	30.3	65.2		L/T	6000	1800	833	---	---
				For R/T Ratios of 7	15	30							
Ti-13V-11Cr-3Al	202	RT	R/L	0.12	0.14	0.17	RT	R/T	53	---	47	44	42
			L/T	60	104	173		L/T	5300	---	775	440	277

(a) Parameters:
R = bead radius
T = sheet thickness
L = bead spacing.

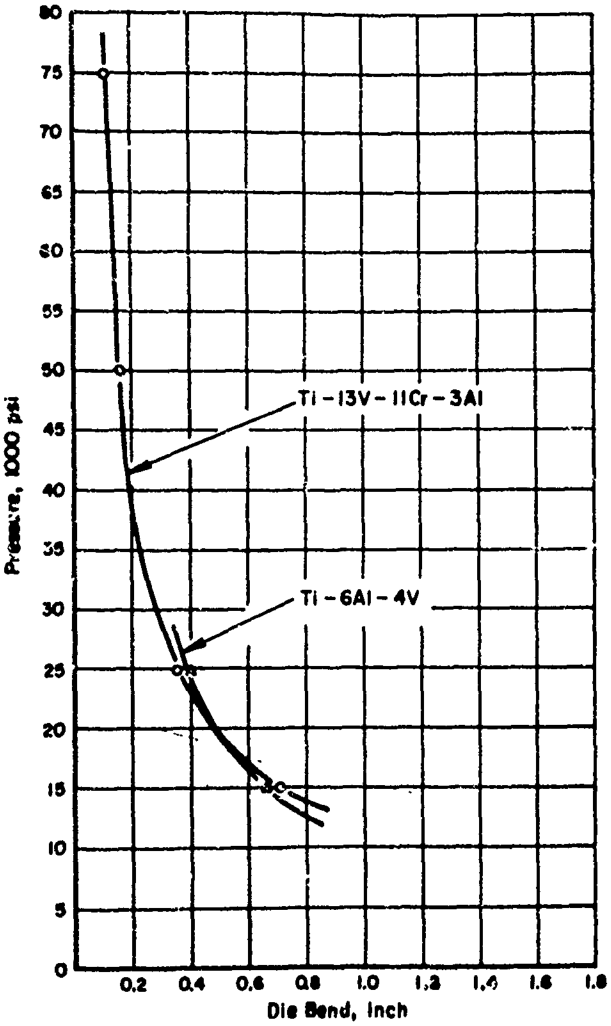

FIGURE 3-18.3-4 EFFECT OF PAD PRESSURE ON RADII THAT CAN BE FORMED AT ROOM TEMPERATURE BY TRAPPED-RUBBER TECHNIQUES IN 0.063-INCH SHEET[2]

cutouts are necessary, the operation should be performed after the part has received a thermal cycle to minimize distortion.

3-18.6 <u>SELECTED REFERENCES ON TRAPPED-RUBBER FORMING</u>

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(5) Wood, W. W., et al., "Volume I and Volume II Final Report on Sheet Metal Forming Technology", Aeronautics and Missiles Division, Chance Vought Corporation, Dallas, Texas, Contract AF 33(657)-7314 (July, 1963).

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(8) Myers, D. E., "DOD High Strength Titanium Alloy Sheet Research Program", North American Aviation, Incorporated, Columbus, Ohio, Navy BuWeps Contract NOas 57-785d Final Report (1963).

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(10) Langlois, A. P., Murphy, J. F., and Green, E. D., "Titanium Development Program, Volume III", General Dynamics/Convair, San Diego, California, Report ASD TR 61-7-576, May 1961, Final Technical Eng. Rpt. for USAF, Contract AF 33(600)-34876 (December 1957-May 1961).

3-19 Tube Bulging

3-19.0 INTRODUCTION

Bulging is a method of forming cylindrical bodies by applying an internal pressure exceeding the yield strength of the material and expanding the tubing to the desired shape. The internal pressure can be delivered by expanding a segmented punch or by a fluid, rubber, or other elastomer. The process is characterized by the use of simple low-cost tooling and is capable of forming an acceptable part in one step. The process is normally limited to the forming of materials in the annealed condition.

The types of bulge forming that can be applied are die forming and free forming, shown in Figure 3-19.0-1. As the names imply, the die-formed component is made in a die that controls the final shape, while the free formed part takes the shape that will contain the internal pressure.

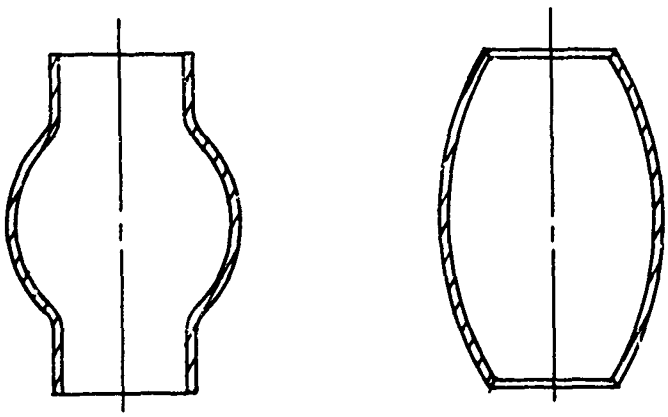

FIGURE 3-19.0-1. COMPARISON OF CONFIGURATIONS BETWEEN DIE AND FREE-FORM TUBE BULGING[1,2]

3-19.1 EQUIPMENT SETUP AND TOOLING

A large number of processes may be used for bulge forming of tubing. Tube bulging is feasible by both conventional (low deformation speed) and high-velocity (high deformation speed) processes.

Conventional processes for bulge forming apply internal pressure to the tubing at a slow rate by the motion of mechanical and hydraulic presses. A liquid or semiplastic filler material is normally used inside the tube so that a hydrostatic pressure is approached. The behavior of the filler material will control how closely the hydrostatic conditions prevail during forming operations. The use of a rubber filler is shown in Figure 25 for bulge forming a tube.

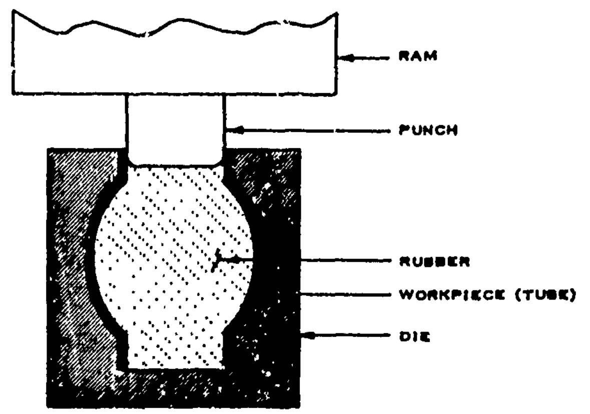

FIGURE 3-19.1-1. RUBBER BULGING SETUP[1,2]

When the ram has been retracted, the rubber returns to its original diameter so that it may be withdrawn from the tube. This technique is in common usage, since it does not have the sealing difficulties associated with the use of a liquid filler. The use of low-melting-point solids, such as Wood's Metal, as filler materials has shown promise for producing large deformations. In this process, the ram applies axial force to the tube as well as pressure to the filler. As the forming progresses, additional tubing material is fed into the die, which accounts for the greater amounts of deformation possible with this technique.

The expanding-mandrel tube-bulging technique is generally restricted to high-production applications because of the cost of the mandrels. The contact of the metal mandrel with the tubing limits the force that can be applied and the maximum deformation that can be obtained with this technique.

Some of the high-velocity techniques that have been applied to tube bulging with the greatest success have used low explosives and electric discharges as energy sources. The electric-discharge techniques have used pressure transducers of electric sparks, exploding bridge wires, and magnetic coils. All of these energy sources, except magnetic forming, require some medium (generally water) to transmit the pressure to the tubing. For maximum efficiency, a closed system is used, which complicates the use of the system from the standpoint of sealing. Sealed systems also require the removal of air from between the tube and the die to prevent high temperatures and burning due to entrapped air. Shock-wave reflectors have been used with low-explosive and electric-discharge systems to obtain unusual free-formed tubing shapes.

Magnetic forming is the only metalworking process that does not require direct contact of a forming medium with the tubing. Consequently, limitations on forming due to friction encountered in most processes does not occur. Also, since the process does not require any forming medium, there is no requirement for massive tooling to contain the force generated in the tubing.

If the pressure for deforming a tube is considered to be hydrostatic in nature, then the pressure required to initiate deformation can be determined from

$$P = 2tS/d$$

where

P = pressure, psi
t = tube wall thickness, inches
S = the flow stress of the tube material, psi
d = the tube diameter, inches.

Since this equation only supplies information on pressure requirements at the start of deformation, some modification is required to present the total picture. As the tube is stretched, the flow stress will increase because of work hardening of the material. At the same time, the diameter, d, will increase and the thickness, t, will decrease. If the final or maximum pressure is required, the conditions that prevail after the tube is formed should be considered in the equation.

3-19.2 MATERIAL PREPARATION

Because of very limited applications of titanium tubing in aircraft in the past, little information has been generated on forming of titanium tubing. Formed tubing has generally been made from roll-formed and welded sections. Some difficulty has been experienced in obtaining sufficient ductility in the heat-affected weld zone for bulge forming operations. Some of the difficulty may have been caused by improper manufacturing practices. The weld beads are normally planished before they are bulge formed. Where possible, the cylindrical preforms are also stress relieved.

3-19.3 BULGE-FORMING LIMITS

Two limitations must be considered in bulge-forming operations: ductility of the workpiece material and tooling. The material ductility will determine the maximum percentage stretch as determined from the following equation:

$$\text{Percent stretch} = \frac{d_1 - d_o}{d_o} \times 100,$$

where

d_o = the original diameter
d_1 = the final diameter.

The percent-elongation values obtained from tensile tests cannot be used to determine this limitation, since only uniform elongation is of practical interest. If necking occurs, as in the tensile test, the bulged tubing component would be scrapped because of excessive metal thinning.

Tooling can affect the percent stretch due to the constraints it places on metal movement. If extra material is drawn in from the ends of the tubing or the length of the tubing is shortened during forming, additional stretching is possible. The percent stretch can sometimes be increased by applying an axial load to the tube to assure feeding additional material to the bulged section.

Another limitation besides percent stretch is the bending strain that occurs if the tube is bulged over too tight a bend radius. This condition results in splitting. The minimum bend radii in the tube forming should not be less than that used in other forming operations, such as brake forming.

If the bulged portion of a tube is considered as a bead, the strain for any given die design can be determined. The severity of deformation is determined by the amount of stretching and the amount of bending. Consequently, the radius at the entrance to the bulged areas as well as the diameter of the bulged section are important considerations in establishing design limits in bulge forming. A section through a bulged portion of a tube is shown in Figure 3-19.3-1, so that the necessary dimensions that control the strain can be analyzed. The radius of entrance to the bulge section is given as r_1, while the depth of the bulge is the dimension H. W is the dimension between tangent points on the bulge.

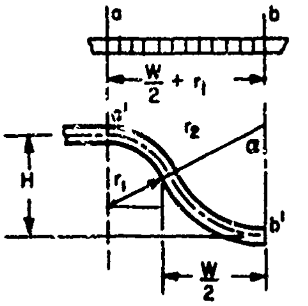

FIGURE 3-19.3-1 BULGE CONFIGURATION AND GEOMETRICAL PARAMETERS[1,2]

The strain ϵ_A can be determined from the following:

$$\epsilon_A = \left\{ \left[\frac{1 + 4\left(\frac{r_1}{W}\right) + 4\left(\frac{r_1}{W}\right)^2 + \left(\frac{H}{W}\right)^2}{4\left(\frac{H}{W}\right) + 8\left(\frac{H}{W}\right)\left(\frac{r_1}{W}\right)} \right] \mathrm{sm}^{-1} \left[\frac{4\left(\frac{H}{W}\right) + 8\left(\frac{H}{W}\right)\left(\frac{r_1}{W}\right)}{1 + 4\left(\frac{r_1}{W}\right) + 4\left(\frac{r_1}{W}\right)^2 + 4\left(\frac{H}{W}\right)^2} \right] \right\} - 1$$

The geometric parameters are identified in Figure 3-19.3-1. The relationships between ϵ_A, H/W, and r_1/W are shown in Figure 3-19.3-2, so that laborious calculations need not be carried out for each new design.

For example, consider the case of a bulge width, W, of 2 inches and an entrance radius on the die of 0.40 inch, which gives an $r_1/W = 0.2$. If a bulge height of 0.50 inch is required, then the $H/W = 0.25$. From Figure 3-19.3-2, the axial strain ϵ_A is found equal to 0.075 in./in. The combined strain $\epsilon_A + Br_1$ determines failure limits, so that the limiting bending conditions must be considered for the particular alloy of interest. This limit, based on r_1/t or bend radius over material thickness, is the same as for brake forming.

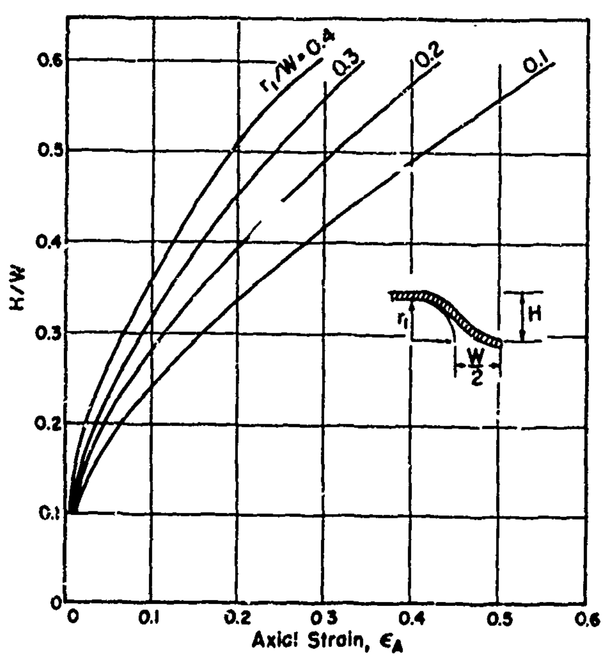

FIGURE 3-19.3-2 H/W VERSUS AXIAL STRAIN ϵ_A FOR VARIOUS VALUES OF r_1/W[1,2]

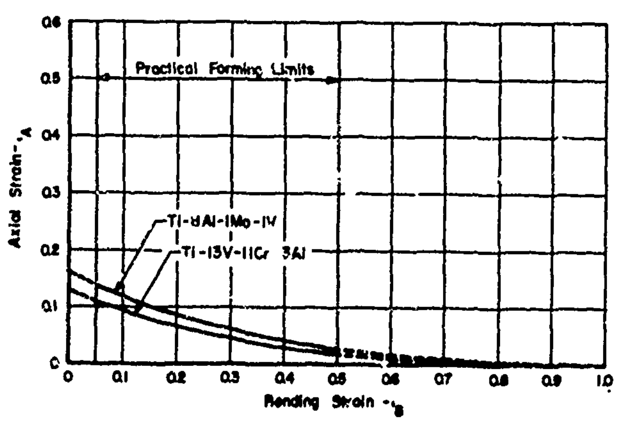

FIGURE 3-19.3-3 COMPOSITE OF BEAD-FORMING LIMITS[3]

A limit between stretching strain and bending strain for two titanium alloys is shown in Figure 3-19.3-3. These curves indicate that a part with a stretching strain of 0.1 in./in. should have a bending strain of less than 0.1 in./in.

Care must be used in applying this technique to determine design limits for a particular material. The established criterion for this analysis is based on no axial movement of material from the ends of the tube into the die. Where such movement is possible, the axial strain will be reduced from that indicated. The analysis does not consider the case of an eccentric forming operation, which will have a different strain from that considered here.

Additional information on tube forming is required and should be obtained through development programs with the specific alloys to be used as tubing. In the absence of additional specific information, the only approach is to predict bulge-forming limits for tubing from data for uniform elongation and permissible bend radii obtained on sheet.

3-19.4 SELECTED REFERENCES ON TUBE BULGING

(1) Wood, W. W., et al., "Volume I and Volume II Final Report on Sheet Metal Forming Technology", Aeronautics and Missiles Division, Chance Vought Corp, Dallas, Texas, Contract AF 33(657)-7314 (July, 1963).

(2) Wood, W. W., et al., "Final Report on Advanced Theoretical Formability Manufacturing Technology", Volume I and II, LTV Vought Aeronautics Division Ling-Temco-Vought, Inc., Dallas, Texas, Contract AF 33(657)-10823 (January, 1965).

(3) Kervick, R. J., Springborn, R. K., Cold Bending and Forming Tube and Other Sections, American Society of Tool and Manufacturing Engineers, Dearborn, Michigan (1966).

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3-20 Tube Bending

3-20.0 INTRODUCTION

The four major methods in general use for bending tubes are: (1) ram or press bending, (2) roll bending, (3) compression bending, and (4) draw bending. Ram or press bending is accomplished by placing the tube between two supports, thus forcing the tube to bend around the ram. Roll bending consists of passing the tube through a suitable series of grooved, power-driven rolls to accomplish the bending. In compression bending, both the tube and the die are stationary, and a wiper die is utilized to wrap the tube around the stationary bend die. The first three methods are used for heavy-wall tubing and are outside the area of interest in aircraft structures. Consequently, only the fourth method--draw bending--is discussed here.

3-20.1 EQUIPMENT SETUP AND TOOLING

Draw bending is predominantly used to bend thin-walled titanium tubing. The tube is confined in the bend; wiper and clamp dies are illustrated in Figure 3-20.1-1. Internal support is provided by a multiball mandrel to prevent collapse of the tubing. Prior to bending, a clamping plug is inserted in one end of the tube. The tube then is placed in the die cavities, and the other end of the tube is pushed over the mandrel. As the clamp die is closed, a cleat on the die is pressed into the tube and clamp plug, crimping the tube and preventing it from slipping during forming. The mandrel is forced through the tube so that its nose is in line with the tangent of the bend die. Then the pressure die is closed.

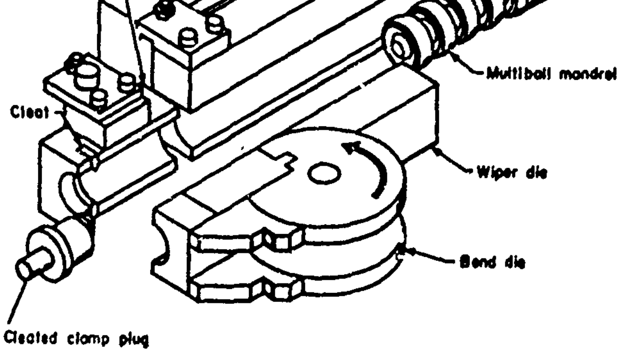

FIGURE 3-20.1-1. TYPICAL TUBE-BENDING TOOLS[1]

During draw forming, the bend and clamp dies are rotated, drawing the tube over the stationary mandrel into the bend area. The stationary wiper die and the bend die confine the inside of the bend and permit the mandrel balls to iron out wrinkles as they occur. The pressure die travels with the tube and provides the reaction force necessary for bending.

The pressure-die boost cylinder is a special attachment considered necessary for bending titanium tube. It applies a load to the end of the pressure die, which reduces the tension stress on the outside of the elbow and moves the neutral axis outward so that only 50 percent of the tube is in tension. Thus, only about 33 percent elongation is required to produce a 1-1/2-D bend (centerline radius) with this system. This amount of elongation is well within the elevated-temperature properties of the commercially pure titanium. The speed of the pressure-die boost system must be coordinated with bending speed to avoid sliding friction between the pressure die and the tube.

Titanium tube is bent in commercially available equipment that has been modified to accept heated tooling. The diameter of the tube dictates the equipment size.

Most tooling materials have a great chemical affinity for titanium and gall under the high loads produced in tube bending. The situation is not greatly alleviated by the conventional lubricants normally used for tube bending.

SAE 4340 steel heat treated to Rockwell C 45 to 48 is adequate for the pressure die because it does not slide against the tube. The wiping die and mandrel that are subjected to sliding friction should be made from aluminum bronze (AMPCO 21).

3-20.2 TUBE-HEATING METHODS

The Grade A-40 titanium tubes that must be bent at elevated temperature normally are not preheated. Experience has shown that the tube rapidly attains the proper temperature when placed over a preheated mandrel and confined in a preheated pressure die. The same should apply to titanium alloy tubing.

The tools used for elevated-temperatures tube bending are usually heated by electric cartridge-type heaters. Electric cartridge heaters have a coiled resistance wire wound on a threaded, refractory core.[2] The core and wire are embedded in a mass of magnesium oxide or similar refractory cements and encased in an Inconel sheath. The units are designed to operate at relatively high temperatures and watt densities. This method of heating is reliable, inexpensive, requires little maintenance, and gives the desired control of temperature.

To handle the heated tubes, the tube bender must be suitably insulated to prevent excessive temperatures at the bearings and also supplied with electrical leads to supply power to the electric cartridge heaters. The heated pressure dies may be insulated with Transite to prevent excessive heat transfer to the pressure-die backup carriage bearings. Electrical leads run directly from bus bars on the pressure die, which supply power to the cartridge heaters, to the powerstat carts.

The powerstat cart consists of two controllers and two variable transformers, one each for the mandrel and pressure die. The temperature is monitored by thermocouples. The powerstats are supplied with 440-volt, 30-amp electrical power.

Only the mandrel bodies are heated. The mandrel balls are not heated because forming is essentially completed by the time the balls come into contact with the tube.

3-20.3 TUBE PREPARATION FOR BENDING

Tubes straight within 0.030 inch per foot give good bending results and are normally purchased to that specification. Straightening tubes prior to bending can reduce the elongation limits of the material by as much as 20 percent. Annealing after straightening or welding would not solve the problem, since the tube again would warp during the annealing operation and additional straightening or sizing would be required.

The diameters of the tubes to be bent must be held within +0.0025 to 0.007 inch, and the ovality should be within 6 percent of the nominal tube diameter. These rather close tolerances are necessary to ensure proper confinement of the tubes by the bending tools.

Many conventional lubricants do not provide the continuous film needed to separate the tools from the workpieces under the high bending loads involved. Ineffective lubrication causes galling of titanium tubes. Experiments indicate that greases with high graphite contents should be suitable for bending titanium at elevated temperatures. In production operations, however, such lubricants have not been completely satisfactory, and minor galling frequently occurs. A phosphate conversion coating is, therefore, used on tubes to supplement graphite-grease lubricants.

3-20.4 TUBE BENDING LIMITS

A number of refinements to the conventional process are required when Grade A-40 (commercially pure) titanium, thin-walled tubing are being bent. Elevated temperatures are generally required for tube sizes above about 2-1/2 inches in diameter, as shown in Table 3-20.4-1. The available data and experience indicate that the best ductility for bending commercially pure titanium is obtained between 350 and 400 F. The ductility also is high and the strength even lower at temperatures above 1000 F; at these higher temperatures, the problems of heating the dies without damaging the bending equipment and providing adequate lubrication are greatly compounded.

The commercially pure Grade A-40 titanium tends to deform locally under tensile loads, especially if they are not applied uniformly. For this reason, tube-bending speeds must be kept low; speeds of 1/4 to 4 degrees/min have been used to produce satisfactory parts. It should be kept in mind that after the bending speed is set, the pressure-die boost system also must be adjusted to provide a uniform thrust and to insure that satisfactory bends will be formed.

Bend quality can also be adversely affected by excessive wear of the mandrel and wiper die. If the mandrel body and balls and the wiper die are allowed to wear down more than 0.005 to 0.008-inch, the tools will not confine the tubes adequately. Thus, large pressure-die forces must be used, and the amount of elongation required to form the parts will be increased. This results in high failure rates.

TABLE 3-20.4-1. BENDING LIMITATIONS FOR GRADE A-40 TITANIUM TUBING[3]

Tube Diameter, inch	Wall Thickness, inch	Minimum Bend Radius, inch	Preferred Bend Radius, inch	Maximum Bend Angle[a], deg: Minimum Bend Radius	Maximum Bend Angle[a], deg: Preferred Bend Radius
Room-Temperature Bending					
1-1/2	0.016	2-1/4	3	90	120
	0.020	2-1/4	3	100	160
2	0.016	3	4	80	110
	0.016	3	4	100	150
2-1/2	0.016	3-3/4	5	70	100
	0.020	3-3/4	5	90	140
	0.035	3-3/4	5	110	180
Elevated-Temperature Bending					
3	0.016	4-1/2	6	90	120
	0.020	4-1/2	6	110	160
	0.035	4-1/2	6	130	180
3-1/2	0.016	5-1/4	7	90	120
	0.020	5-1/4	7	[illegible]	160
	0.035	5-1/4	7	130	180
4	0.020	6	8	110	160
	0.035	6	8	120	180
4-1/2	0.020	6-3/4	9	130	140
	0.035	6-3/4	9	140	140
5	0.020	10	10	--	110
6	0.020	12	12	--	100

(a) Bend angle is predicated on a clamp section 3 times as long as the tube diameter and on maximum mandrel-ball support.

3-20.5 SELECTED REFERENCES ON TUBE BENDING

(1) Kollmorgen, L. L., "Titanium Tube Bending", Technical Paper No. 616, American Society of Tool and Manufacturing Engineers, Collected Papers, Metal Forming, Volume 64, Book 4, 1964 Library Edition, The Boeing Company, Seattle, Washington.

(2) Langlois, A. P., Murphy, J. F., and Green, E. D., "Titanium Development Program, Volume III", General Dynamics/Convair, San Diego, California, Final Technical Engineering Report, Contract AF 33(600)-34876 (May, 1961).

(3) Killmorgen, L. L., "How to Bend Titanium Tubing", The Tool and Manufacturing Engineer, 52 (4), 90-92 (April, 1962).

(4) Kervick, R. J., Springborn, R. K., Cold Bending and Forming Tube and Other Sections, American Society of Tool and Manufacturing Engineers, Dearborn, Michigan (1966).

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3-21 Drop-Hammer Forming

3-21.0 INTRODUCTION

Drop-hammer forming is a progressive deformation process for producing shapes from sheet metal in matched dies with repetitive blows. The process offers advantages for a variety of parts that are difficult or uneconomical to produce by rubber- and contour-forming techniques. Typical applications include beaded panels and curved sections with irregular contours. Drop hammers are often used for details such as half sections of tees or elbows that can be joined together later. The process is best suited to shallow-recessed parts because it is difficult to control wrinkling without a blank holder. Nevertheless, many deeply recessed parts, especially those with sloping walls, are made on drop hammers.

The impact-loading characteristic of drop hammers is not well suited to forming some strain-rate-sensitive materials. To work such metals, the operator must limit the maximum velocity of the ram.

3-21.1 EQUIPMENT SETUP AND TOOLING

The gravity drop hammer is equipped with a weight or ram that is lifted by means of some device such as a rope or a board, and then permitted to drop unrestricted. The pneumatic hammer, shown in Figure 3-21.1-1, and the steam hammer are equipped with a pressure cylinder that lifts the ram and also adds energy to that of the falling ram. The drop hammer is fundamentally a single-action press. It can be used, however, to perform the work of a press equipped with double-action dies through the use of rubber blankets, beads in the die surfaces, draw-rings, and other auxiliary measures.

The platen sizes of commercially available drop hammers vary from 21 x 18 in. to 120 x 96 in. The smaller machine has a ram weight of 600 pounds and a maximum die weight of 600 pounds, which gives a possible energy level in free fall of 2900 ft-lb. The larger drop hammer has a ram weight of 33,000 pounds and a maximum die weight of 47,000 pounds, which gives a possible energy level in free fall of 90,000 ft-lb.

The basic tool materials for drop-hammer forming are Kirksite and lead. Lead is preferred for the punches since it will deform during service and conform to the female die. For room-temperature forming of titanium, an uncapped lead punch may have a useful like of about five parts. The wide use of Kirksite as a die material stems from the ease of casting it close to the final configuration desired. Most companies doing a large amount of drop-hammer work prepare the tooling in their own foundry. Beryllium copper dies have been used for drop-hammer forming, but generally the additional cost is not warranted. Ductile iron and steel dies are used where the tooling must be heated above 400 F.

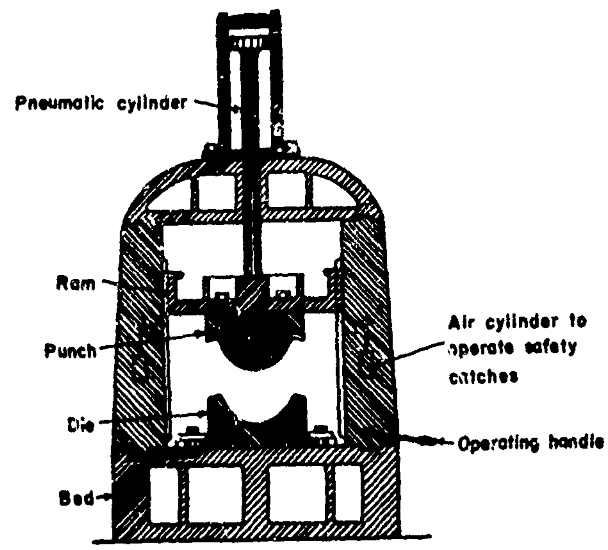

FIGURE 3-21.1-1. PNEUMATIC-HAMMER(1)

Contact between titanium and low-melting tooling materials such as lead or Kirksite should be avoided. This is especially true when the titanium is formed at elevated temperatures or must receive a thermal treatment after forming. The low-melting die material, which rubs off on the titanium surface during forming, will contaminate the material and render it structurally unsatisfactory. Several techniques have been used to overcome this difficulty. The die and punch may be capped with sheet steel, stainless steel, or Inconel to prevent pickup on the titanium. The choice of capping material depends on the punch life desired. Inconel gives the best life in sheet thicknesses of 0.025 to 0.032 inch.

Sometimes two punches are used: a working or roughing punch and a coining or finishing punch. When the working punch becomes excessively worn, it is replaced by the coining punch, and a new coining punch is prepared. Another method of achieving the same results with one punch is to use rubber pads. Rubber suitable for this purpose should have a Shore Durometer hardness of 80 to 90. Figure 3-21.1-2 indicates the positioning of pads for a particular part. The maximum thickness of rubber is situated where the greatest amount of pressure is to be applied in the initial forming. As the forming progresses, the thickness of rubber is reduced by removing some of the pads after each impact. Rubber pads are not very satisfactory for elevated-temperature forming because of rapid deterioration at the temperatures required for forming titanium (1000 F).

For room-temperature forming of smoothly contoured parts, Kirksite dies suitably shielded with

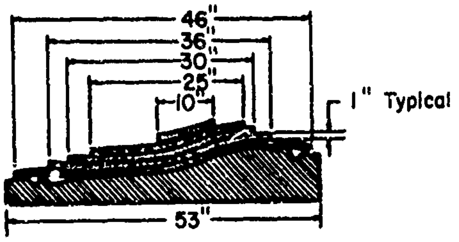

FIGURE 3-21.1-2. POSITIONING OF RUBBER BLANKETS(1)

The blank would be placed between the die and the first pad.

steel or stainless steel can be used. Steel inserts should be used in sharply radiused corners of the dies. For complicated parts, cast steel or high-silicon-cast-iron dies give better die life.

Mating surfaces of the die set must make contact uniformly to avoid canning and warping, defects which are difficult to remove in subsequent forming. Hence, male and female dies should be carefully blued-in with allowance for the sheet to be formed.

Difficult titanium parts are formed at elevated temperatures (800 to 1000 F). For hot operations, the thermal expansion of the blank and tooling must be considered. If the tooling is not heated, the amount it expands will depend on the length of time it is in contact with the blank. The thermal expansion value used in the design of tooling for titanium is 0.006 in./in. for temperatures between 70 and 1000 F. The allowance for expansion of circular or elliptically shaped parts should be made radially, not peripherally. When a hot-sizing operation is to be performed after forming, the drop-hammer tooling is generally made to net dimensions without consideration of thermal expansion.

If the blanks are to be heated in a furnace and then transferred to the drop-hammer tools, stops should be located in the tooling for rapid and precise location of the blank. Resistance heating may be used in drop-hammer forming but generally requires more time for forming each part due to the electrical connections necessary. Clearance relief for the electrical leads is necessary if the blank is shorter than the die. The dies must be insulated from the bed of the press to prevent short circuiting. Insulation materials such as Transite or high-temperature rubber have been used satisfactorily for this application. A typical arrangement for resistance heating on the drop hammer is shown in Figure 3-21.1-3. This heating technique is generally applied to long slim parts with the current passing through the long dimension of the blank.

When titanium parts cannot be readily formed with one blow in one die set, better results can sometimes be obtained by introducing two-stage tools, each of which permits one-blow forming, rather than using multiple blows in one set of tools. In such cases, good results can be obtained by making the part slightly oversized in the first-stage tools and obtaining the final shape by a coining operation in the second set of tools.

3-21.2 BLANK PREPARATION

The blanks for drop-hammer forming are generally rectangular in shape and are prepared by shearing. The blank should be large enough to yield a part with a 2- to 3-inch-wide flange in order to facilitate drawing of the metal during forming. Where multistage forming is used, the part may be trimmed so that only a 1/2-inch-wide flange is left for the final forming stage.

Sheared edges are generally satisfactory for drop-hammer forming since the wide flange permits some cracking in the area without harming the part. The blank should, however, be deburred to reduce possible damage to the tooling.

Lubricants used in drop-hammer forming of titanium should be of the nonchlorinated types(2). Extreme-pressure oils, pigmented drawing compounds, and nonpigmented drawing compounds are used in most operations. Some of the specific lubricants that have been used in drop-hammer forming of titanium are Dag-41 and Everlube T-50. The lubricants are generally swabbed onto the blank surface prior to forming, but for elevated-temperatures forming it is best to place the lubricants on the die surfaces. The lubricants should be removed from the parts surface as quickly as possible after the parts are formed. Complete removal is necessary before any subsequent thermal treatment.

3-21.3 BLANK HEATING METHODS

Furnaces used to heat blanks should be controlled within 15 F to prevent possible damage to the titanium. The temperature to be used depends on the titanium alloy being formed. Care must be exercised to assure that the parts are not overheated, and the parts should be shielded so that no hot spots occur. As soon as the blank reaches the required temperature, it should be removed from the furnace and formed. The furnace should be located beside the hammer. The total time for the sequence of transfer, forming, and return to the furnace should not exceed 8 seconds.[3] After the final strike on the hammer, the dies should remain closed for about 30 seconds so that the part will cool slightly in the die. Care should be exercised in elevated-temperature forming of titanium that the total time at temperature does not exceed that permitted for the alloy. The use of an inert furnace atmosphere increases the permissible time at temperature but should not be depended on in place of efficient operations.

Resistance-heating methods, as shown in Figure 3-21.1-3, require high-temperature rubber pads attached to the ends of the tool so that the blank is not in contact with the tool during heating. The electrodes are clamped to each end of the blank so that the current must pass through the entire blank. Clamping should be secure so that current leakage at the clamp-blank interface will not result in hot spots and possible melting due to insufficient clamping area for the current being transmitted. The current supplied from a low-voltage, high-amperage source, such as a welding machine, is increased until the desired temperature of the blank is obtained. The temperature of the blank can be checked with a thermocouple. The use of temperature-sensitive crayons is permitted only on the trim areas of the part to avoid possible contamination of the part. As soon as the forming temperature is reached, the blank can be covered with a high-temperature rubber pad at least 1 inch thick; the electrodes are disconnected and the part is then formed. This

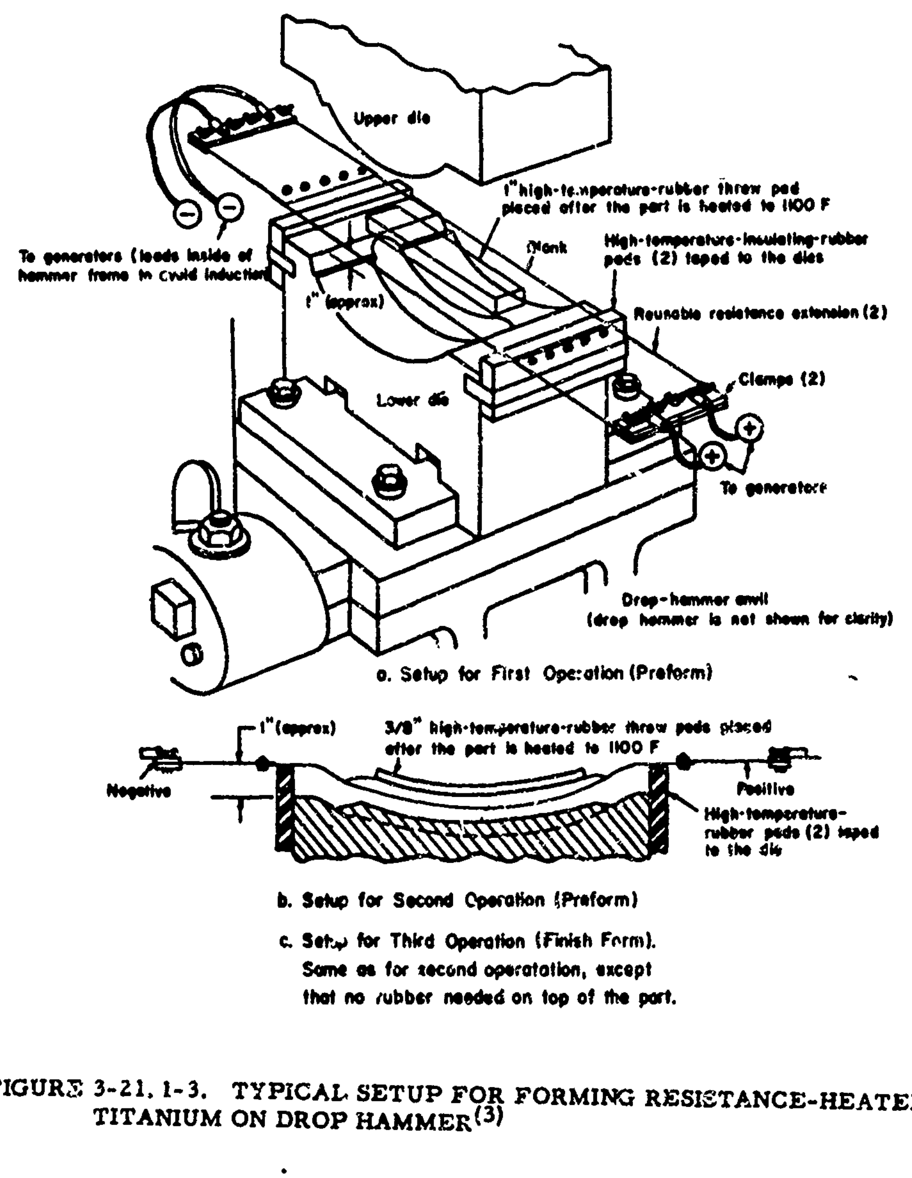

FIGURE 3-21.1-3. TYPICAL SETUP FOR FORMING RESISTANCE-HEATED TITANIUM ON DROP HAMMER[3]

process is repeated for each successive blow until the part is formed to final dimensions. In the final stage, no rubber is used over the part and the dies are closed on the part for at least 30 seconds after the final blow.

A third method of heating titanium for drop-hammer forming is with radiant quartz lamps. The lamps are placed close to the blank while the blank is resting on the tooling. The lamps are then moved out of the way, and the part is formed. This sequence is repeated until the part is completely formed. It sometimes helps if the edges of the blank are supported on an insulating blanket, such as asbestos, so that the heat loss to the tooling is reduced. Quartz-lamp heating of a flat surface is very effective. After the part has been formed partially, however, it is difficult to control the amount of heat the surface of the part receives. After initial heating, it may be necessary to use furnaces to obtain the desired results.

3-21.4 DROP-HAMMER FORMING LIMITS

The severity of permissible deformations in drop-hammer forming is limited by both geometrical considerations and the properties of the workpiece material. The forming limits can be predicted by considering parts of interest as variations of beaded panels. For parts characterized in this way, the critical geometrical factors are the bead radius, R, the spacing between beads, L, and the thickness of the workpiece material, T. These parameters are illustrated in Figure 3-21.4-1.

Two of the forming limits depend entirely on geometry and are the same for all materials. The ratio of the bead radius, R, to bead spacing, L, must lie between 0.35 and 0.06. The lower formability limit is controlled by the necessity for producing uniform stretching and avoiding excessive springback. If the R/L ratio is too small, there will be a greater tendency for localized stretching at the nose of the punch. Furthermore, the material may deform elastically, not plastically, and springback will be complete when the load is removed.

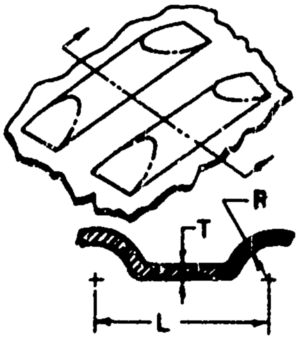

FIGURE 3-21.4-1. PARAMETERS OF DROP-HAMMER BEADED PANELS[4]

Within the limits set for all materials by the R/L ratio, success or failure in forming beaded panels depends on the ratio of the bead radius to the sheet thickness, R/T, and on the ductility of the workpiece material. The part will split if the necessary amount of stretching exceeds the ductility available in the material. The splitting limit can be predicted from the elongation value, in a 0.5-inch gage length, in tensile tests at the temperature of interest. The variation of the drop hammer formability index for two titanium alloys with temperature is given in Figure 3-21.4-2. It is obvious from this curve that significant increases in formability of the titanium alloys shown can be achieved at temperature above 1000 F.

Formability limits for two titanium alloys are shown in Figures 3-21.4-3 and 3-21.4-4. The charts show the marked improvements in formability resulting from better elongation values at elevated temperatures. Although the limits apply to beaded panels, they can be used with caution as guides to forming other types of parts with drop hammers.

Earlier, other investigators[5] suggested the stretching limits for drop-hammer forming given in Table 3-21.4-1. The parts used in that study were more complex than beaded panels. Their limits are more conservative than those indicated in Figures 3-21.4-3 and 3-21.4-4. The minimum thickness for hammer-formed parts of titanium alloys is about 0.025 inch. Heavier stock should be used for more complex shapes. It is difficult to predict proper springback allowances for complex parts. Therefore, the general practice is to hot size them after hammer forming. In general, the tolerance for parts formed on drop hammers is about 1/16 inch.

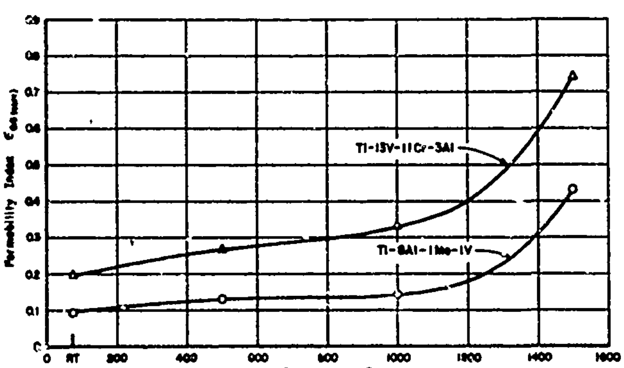

FIGURE 3-21.4-2. OPTIMUM FORMING TEMPERATURE CURVES FOR DROP-HAMMER FORMING[5]

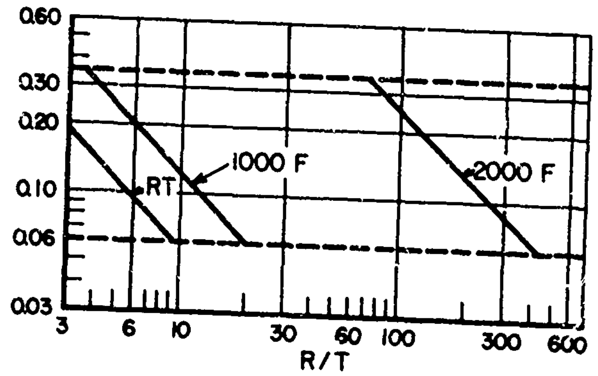

FIGURE 3-21.4-3. LIMITS FOR FORMING BEADED PANELS FROM THE Ti-8Al-1Mo-1V ALLOY WITH A DROP HAMMER[4]

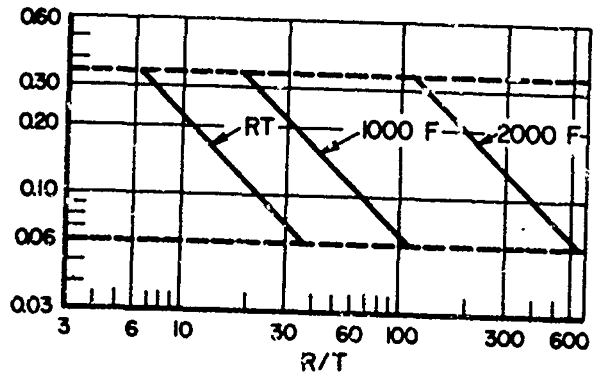

FIGURE 3-21.4-4. LIMITS FOR FORMING BEADED PANELS FROM THE Ti-13V-11Cr-3Al ALLOY WITH A DROP HAMMER[4]

TABLE 3-21.4-1. DROP-HAMMER MAXIMUM STRETCH LIMITS FOR VARIOUS TITANIUM ALLOYS[5]

Material	Condition	Maximum Stretch[a] at 900 F
13V-11Cr-3Al	Solution treated	15.8
8Mn	Annealed	15.8
5Al-2.5Sn	Annealed	12.6
6Al-4V	Annealed	12.6
3.25Mn-2.25Al	Annealed	15.8

(a) Percent stretch = $\frac{L_1 - L_0}{L_0} \times 100$,

where

L_1 = stretched length

L_0 = original length.

3-21.5 SELECTED REFERENCES ON DROP-HAMMER FORMING

(1) Forming of Austenitic Chromium-Nickel Stainless Steels, Second Edition, The International Nickel Company, Incorporated, 67 Wall Street, New York (1954).

(2) Gerds, A. F., Strohecker, D. E., Byrer, T. G., Boulger, F. W., "Deformation Processing of Titanium and Its Alloys", NASA Technical Memorandum NASA TM X-53438, Battelle Memorial Institute, Columbus, Ohio, Contract No. DA-01-021-AMC-11651(Z) (April 18, 1966).

(3) Achbach, W. P., "Forming of Titanium and Titanium Alloys", TML Report No. 42, Volumes I and II, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (May 18, 1956).

(4) Wood, W. W., et al., "Final Report on Sheet Metal Forming Technology", Volumes I and II, Aeronautics and Missiles Division, Chance Vought Corporation, Dallas, Texas, Report No. ASD-TDR-63-7-871, Contract No. AF 33(657)-7314 (July, 1963).

(5) Handova, C. W. and Winslow, P. M., "Feasibility Study for Producing Welded Airframe Components from Titanium Alloys", Final Report, Volume I, "Research" and Volume II, "Manufacturing", North American Aviation, Incorporated, Los Angeles, California, Report Numbers AL-2702-1 and AL-2702-2, Contract No. AF 33(600)-30902 (October 11, 1957).

3-22 Roll Forming

3-22.0 INTRODUCTION

The term roll forming usually refers to a continuous bending process performed progressively by a series of contoured rolls in a special machine. With equipment of this kind (Figure 3-22.0-1), which can operate at high speeds, tolerances as small as ±0.005 inch can be obtained in cold forming. Roll forming is often used to bend strip into cylinders that are butt welded to produce thin-walled tubing with a relatively small diameter.

3-22.1 EQUIPMENT SETUP AND TOOLING

A schematic drawing of a six-stand Yoder roll-forming machine was shown in Figure 3-22.0-1. The strip, entering from the left, passes through a series of six rolls and emerges from the machine as a rolled shape. The method offers a number of advantages. A bend radius of 1T less than the minimum bend radius in brake forming can usually be attained in roll forming titanium alloys. Parts can be produced with lower internal stresses than are present in parts formed by impact or brake forming. Roll forming is a high-speed, fast-production process. For instance, the man-hour savings by roll forming may amount to 85 percent, compared with brake forming the same shape in 3-foot lengths.

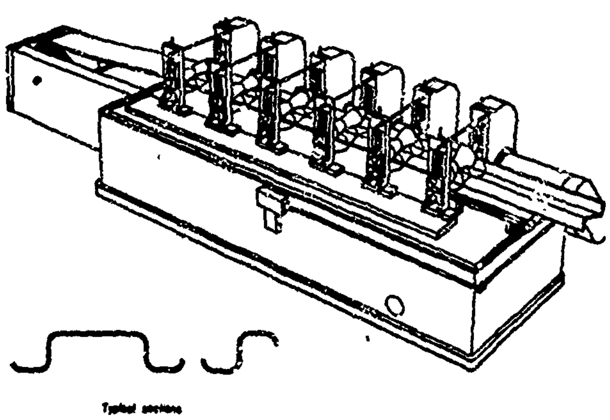

FIGURE 3-22.0-1. SCHEMATIC DRAWING OF ROLL-FORMING MACHINE[1]

Roll-forming machines are operated at speeds up to 125 ft/min. With the recent availability of many of the titanium alloys in strip form,[2] the full potential of roll forming can now be utilized. The availability of strip is particularly important in the case of the stronger alloys that are roll formed at elevated temperatures.

Equipment for roll forming is available from a number of manufacturers in a range of sizes and capacities. The size and weight of the equipment increases as the maximum sheet thickness increases. The number of roll stands required for a particular application depends on the complexity of the bending required. A machine may consist of from 2 to 20 roll stands. Relatively simple bending contours can be accomplished by using six or less rolls. Equipment manufacturers should be consulted on equipment requirements for specific applications.

The power available limits the size of the stock that can be processed. For instance, it was found[3] that a 10-hp mill was incapable of producing 1-1/2-inch hat titanium sections and angles from 0.040 or 0.063-inch stock at a speed of 100 ft/min. However, the same dimensions could be made at 125 ft/min from 0.090-inch stock of the Ti-4Al-4Mo-1V and the Ti-16V-2.5Sn alloys with a standard 50-hp roll-forming unit.

High-temperature bearings are recommended for roll-forming equipment to be operated at elevated temperatures. In one study[4], however, satisfactory results were obtained by replacing the shaft on each stand with hollow shafts through which cooling water was circulated. The tubular shafts were made from chromium-plated 4130 steel. The cooling system kept the bearing temperature below 300 F when the rolls were operating at 1100 F.

The rolls used in roll-forming equipment may be made from a variety of materials. Oil-hardened tool steel rolls are normally used. For high-production applications where long-wearing characteristics are desirable, rolls of steels containing about 0.1 to 0.5 percent carbon and 12 to 13 percent chromium are used. Chromium-plated rolls may be used where high-finish materials are to be formed. Sometimes, duplex rolls are used where only the working surfaces are made of hardened tool steels. They are especially suitable for wide rolls with shallow contours.

Room-temperature roll forming of titanium alloys has been performed with rolls made of AISI-E-52100, high-chromium tool steel.[37]

Rolls used to roll form the Ti-4Al-3Mo-1V alloy at room temperature were case-hardened chromium-molybdenum steel with case depth of 0.090 inch.[5] Others have used rolls fabricated from Class H-13 tool steel - a hot die steel chosen for its hardness, freedom from distortion, and resistance to scaling.[4] These rolls were hardened to 52 to 54 on the Rockwell C hardness scale.

3-22.2 MATERIAL PREPARATION

The general precautions given in other sections on blank preparation should be observed. Especially detrimental in roll forming is the presence of grinding marks and scratches parallel to the length of the strip.[6] Such marks initiate cracking when the strip is formed into shapes. Their effects can generally be minimized by buffing or by a light chemical etch. Removing as little as 0.001 inch of metal by etching ofter significantly increases uniform elongation of titanium.

Variations in the thickness of the metal strip result in dimensional inaccuracy of roll-formed parts. Improvements in thickness and shape control by the metal-rolling mills has minimized this problem.

Lubricants are almost always required for the roll forming of titanium and it alloys. For roll forming at room temperature, fluids such as SAE 60 oil or its equivalent function both as lubricants and coolants. Solid lubricants are often used for roll forming at elevated temperatures. Satisfactory results were obtained when one commercially available lubricant, Dag-41, was thinned with 10 parts of lacquer and sprayed on both sides of titanium-alloy strip prior to rolling at 100 F.[4] Such lubricants also may be applied by dipping, brushing, or wiping. Upon heating to the rolling temperature, the carrier usually vaporizes, leaving the filler as a solid residue to provide lubrication. Another lubricant that is used for elevated-temperature roll forming is Everlube T-50.

3-22.3 BLANK HEATING METHODS

Both the rolls and the titanium strip should be heated in roll-forming operations.[4,7] Experiments with induction heating, gas-fired muffles, and electric muffle furnaces for heating each set of rolls indicated that gas-heated muffles built around each rolling stand were best.

3-22.4 ROLL FORMING LIMITS

Experimental work was done on the room-temperature roll forming of the Ti-4Al-3Mo-1V and the Ti-2.5Al-16V alloys in the solution-treated condition.[3] Studies on producing a 90-degree-angle section resulted in the minimum forming values listed in Table 3-22.4-1. Although the minimum radius was 2.0 T to bend 0.040- and 0.060-inch-thick sheet of the Ti-2.5Al-16V alloy, and 3.0 T to bend the 0.090-inch-thick strip, the springback was approximately equal to that obtained with the Ti-4Al-3Mo-1V alloy, which required a 3 T bend radius for all three thicknesses of sheet. This work indicated that springback is influenced by the pressure applied by the work.

TABLE 3-22.4-1. SUMMARY OF ROLL-FORMING TEST RESULTS ON SAMPLES OF SOLUTION-TREATED ALLOYS AT ROOM TEMPERATURES[(a)(3,5)]

Alloy	Material Thickness, T, in	Minimum T Radius	Average Springback, deg
Ti-4Al-3Mo-1V	0.020	3.0	11.2
	0.020	4.0	14.6
	0.040	3.0	10.4
	0.040	4.0	17.8
	0.040	3.0	3.5
	0.040[(b)]	1.0	0
	0.060	3.0	8.5
	0.060[(b)]	1.0	0
	0.063	3.0	10.8
	0.063	4.0	15.6
	0.090	3.0	14.0
Ti-2.5Al-16V	0.040	2.0	2.0
	0.060	2.0	7.0
	0.090	3.0	15.0

(a) The Ti-2.5Al-16V angles were made in a six-roll machine, the others in a seven-roll machine.
(b) Rolled at 1100 ±25 F.

Experimental work indicates that the solution-treated Ti-6Al-4V alloy can be formed into a hat section at 1100 F.[4]

Some of the newer titanium alloys, such as the Ti-8Al-1Mo alloy, have been roll formed by heating the blanks to about 1000 F and rolling on rolls heated in the range of 200 to 500 F. Up to 20 roll passes with removal of contaminated surface layer between each passes resulted in 1 T bend radii.[7]

3-22.5 SELECTED REFERENCES ON ROLL FORMING

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(2) "Basic Design Facts About Titanium", Reactive Metals, Incorporated, Niles, Ohio, and personal communication with Mr. Dom Strollo, Reactive Metals, Incorporated (April 26, 1965).

(3) Langlois, A. P., Murphy, J. F., and Green, E. D., "Titanium Development Program, Volume III", ASD Technical Report 61-7-576, Final Technical Engineering Report, Convair, General Dynamics Corporation, Contract AF 33(600)-34876, (May, 1961).

(4) Gunter, J. L., "Determination of Adaptability of Titanium Alloys", Final Report, Volume III, "Processes and Parts Fabrication", Boeing Aircraft Co., Seattle, Washington, AMC TR 58-7-574, Contract AF 33(600)-33765, (December 1, 1958); ASTIA Document AD-156058.

(5) Spalding, L. P., "Evaluation of New Titanium Sheet Alloys for Use in Airframe Construction", AMC Report No. 60-7-56, Final Technical Engineering Report, Volume III, Contract AF 33(600)-33597 (December 30, 1960).

(6) Mattek, L. J., "Roll Forming Selected to Ease Titanium Shaping", Metalworking, 17 (8), 50-51 (August, 1961).

(7) Preliminary information reported by D. E. Makepeace Division, Englehard Industries on Contract AF 33(615)-2499.

3-23 Roll Bending

3-23.0 INTRODUCTION

Roll bending is the most economical process for producing single-contoured skins from the titanium alloys. In addition to bending flat sheet into cylindrical contours, the linear-roll-bending technique also is commonly used to curve heel-in and heel-out channel sections with maximum flange heights below 1.5 inches. The channels may initially have been produced by roll forming on a press or even by extrusion. In addition to roll bending, the final contour of a channel or other section are obtained by bending channel sections to the desired contour and then splitting the channels to from the angle sections.

Figure 3-23.0-1 is a sketch of a typical setup for the linear roll bending of channels. The upper roll in the pyramid-type roll configuration can be adjusted vertically as shown in the figure, and the radius of the bend is controlled by the adjustment of this roll. The geometry for heel-in and heel-out channels also is shown in the sketch.

Roll bending is a process that depends greatly on operator technique. Premature failures will occur if the contour radius, R, is decreased in increments that are too severe. On the other hand, too many passes through the rolls may cause excessive work hardening in the channel. An operator usually must form several trial parts of a new material in order to establish suitable conditions.

3-23.1 EQUIPMENT SETUP AND TOOLING

Linear-roll-bending equipment generally is quite simple in design. One common type of equipment utilizes a pyramidal design both in vertical and horizontal machines. Three rolls are used, two lower rolls of the same diameter placed on fixed centers at the same elevation, and a third or upper roll placed above and between the lower rolls. The upper roll may be adjusted vertically to produce different curvatures, and all three rolls are driven.

Another type of equipment for bending shapes is the pinch-type roll bender, so called because its two main rolls actually pinch the stock between them with sufficient pressure to pull the material through against the resistance of the bending stress. This equipment contains four rolls. The upper and lower main rolls are driven by a train of gears and the lower roll, directly beneath the upper one, is adjustable vertically. The large rolls support the flanges of the shape during bending and tend to minimize buckling by supporting the sides of the flanges. The small idler rolls can be adjusted up and down for changing the bend radius.

In addition to rolls for contouring channels and other shapes, equipment also is available for bending sheet sections into shapes. Such equipment is extensively used to bend aircraft skins, wing sections, and the like.

Another type of roll-bending equipment is made specifically for producing cylindrical and other closed sections from sheet. Such equipment is called a slip roll former or bender, and these machines feature pinch-type rolls. They are very versatile and adaptable to many operations. The equipment uses larger diameter rolls than the sheet-forming rolls just described, and is characterized by the ability of the upper roll to swing

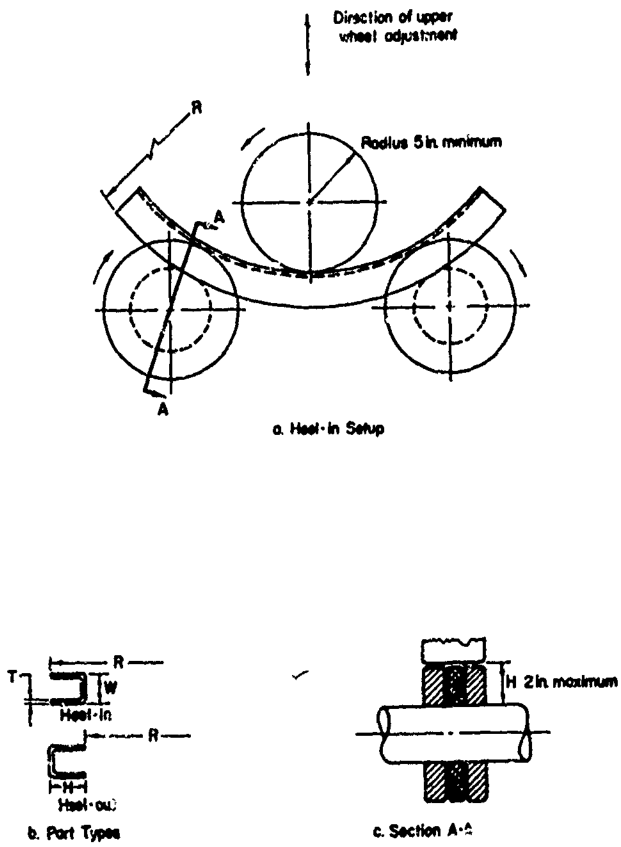


FIGURE 3-23.0-1. PART TYPES AND SETUP FOR ROLL BENDING[1]

open at one end (outboard bearing) to permit easy removal of the completed cylinder or other closed shape without distortion.

Rolls for linear-contour bending of shapes have been made from a variety of materials. Sometimes the rolls are made from hard rubber for use at room temperature. Six-inch-diameter beryllium-copper rolls for bending channels of titanium alloys at room temperature, 400 F, and 800 F have been used.[2] Since those rolls scored badly, beryllium-copper rolls probably are not suitable for use in the production roll bending of titanium and its alloys, especially at elevated temperatures.

The most common materials for the rolls on roll-bending machines are the tool steels. These may range from Grades 0-2 for room-temperature application to Grades H-11 and H-13 for elevated-temperature use.

Rolls for the sheet-roll-bending machines most often consist of low-alloy steels such as Grade 4130 with flame-hardened surfaces. The surfaces usually have a Rockwell C hardness of about 50.

3-23.2 BLANK PREPARATION

The precautions given in previous sections on blank preparation must be observed. For the roll bending of flat sheet of titanium and its alloys, the flatness of the sheet is extremely important. The sheet must be flat within 0.6 percent, as shown in Figure 3-23.2-1. In addition, the corners of the sheet part to be contoured should be chamferred prior to rolling to prevent marking of the rolls.

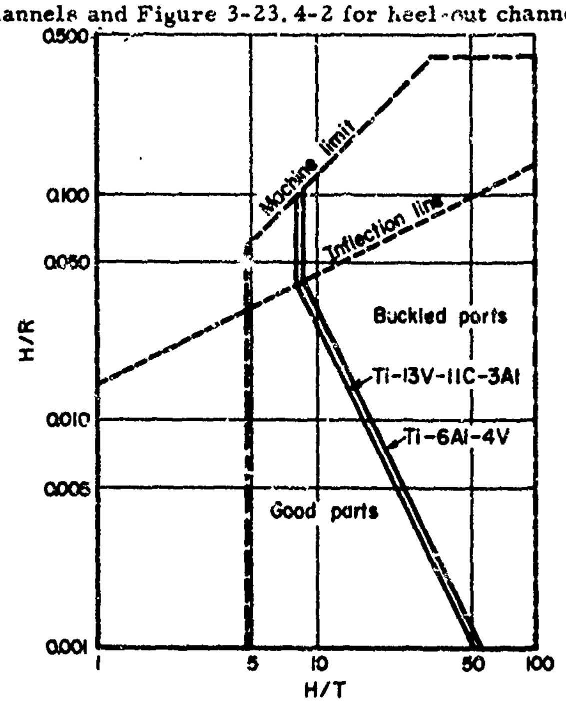
FIGURE 3-23.2-1. TITANIUM-SHEET FLATNESS PARAMETERS FOR ROLL BENDING

3-23.3 BLANK HEATING METHODS

Roll bending of titanium and many of its alloys is done at room temperature whenever possible. However, some of the stronger and stiffer alloys cannot be bent to as small a radius at room temperature as they can at elevated temperatures. Shapes such as channels should be contoured at elevated temperatures. Some experiences with heated rolls have resulted in formed parts with smaller bend radii than those obtained at room temperature.[2]

3-23.4 ROLL-BENDING LIMITS FOR CHANNELS

Transverse buckling and wrinkling, respectively, are the common modes of failure in bending heel-out and heel-in channels. The principal parameters, shown in Figure 3-23.0-1, are the bend radius, R, the channel height, H, the web width, W, and the material thickness, T. The roll bending limit curves for the titanium alloys rolled at room temperature are given in Figure 3-23.4-1 for heel-in channels and Figure 3-23.4-2 for heel-out channels.



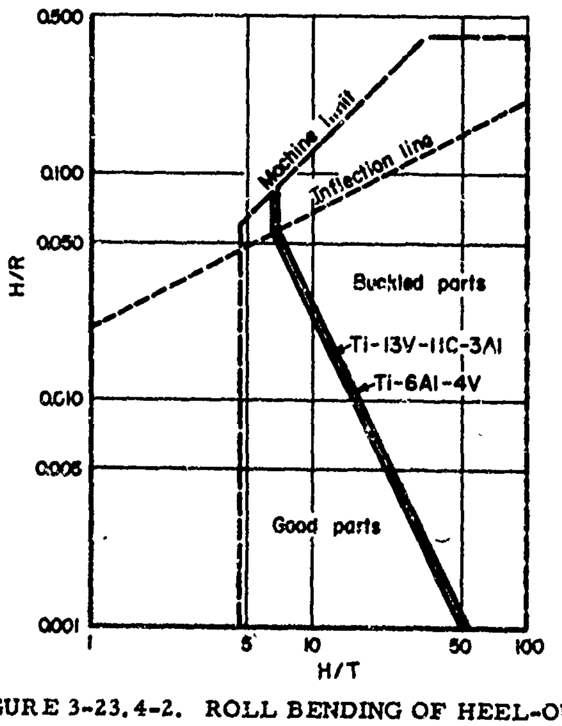


FIGURE 3-23.4-2. ROLL BENDING OF HEEL-OUT CHANNELS FOR TWO TITANIUM ALLOYS (1)

3-23.5 SELECTED REFERENCES ON ROLL BENDING

(1) Wood, W. W., et al., "Theoretical Formability", Volumes I and II, Vought Aeronautics, a Division of Chance Vought Corporation, Dallas, Texas, Contract No. AF 33(616)-6951, Report ASD TR 61-191 (I) and (II) (August, 1961).

(2) Adams, D. S. and Cattrell, W. M., "Development of Manufacturing Techniques and Processes for Titanium Alloys", Final Report, Ryan Aeronautical Company, San Diego, California, AMC TR No. 58-7-539, Contract No. AF 33 (600-31606 (July 3, 1958); ASTIA Document No. AD-156054.

(3) Kervick, R. J., Springborn, R. K., Cold Bending and Forming Tube and Other Sections, American Society of Tool and Manufacturing Engineers, Dearborn, Michigan (1966).

(4) Gerds, A. F., Strohecker, D. E., Byrer, T. G., Boulger, F. W., "Deformation Processing of Titanium and Its Alloys", NASA Technical Memorandum NASA TM X-53438, Battelle Memorial Institute, Columbus, Ohio, Contract No. DA-01-021-AMC-11651(Z) (April 18, 1966).

3-24 Spinning and Shear Forming

3-24.0 INTRODUCTION

Spinning and shear forming are processes for shaping seamless, hollow sheet-metal parts by the combined forces of rotation and pressure. Only minor changes in material thickness occur during spinning; shear forming causes thinning.

Spinning may be classified as manual or power spinning, depending on the manner of applying the force to the blank. Manual spinning is limited to thin (less than 1/16-inch-thick) low-strength (a yield strength under 30,000 psi) workpieces.[1] Power spinning uses mechanical or hydraulic devices to apply greater tool forces to the blank and can consequently be used to form thicker and stronger materials.

Shear-forming processes can be broken down into cone and tube shear forming. Any shapes other than a tube will be considered under cone or modified cone shapes, such as hemispheres.

A typical example of cone shear forming is shown in Figure 3-24.0-1. The blank is a circular disk, which is clamped to the rotating mandrel by the tailstock. Two rollers located at opposite sides of the mandrel apply a force along the axis of the mandrel and force the blank to take the shape of the mandrel. Figure 3-24.0-1 shows a progression of the forming sequence, starting from top to bottom. The rolls are not driven but rotate because of contact with the rotating blank.

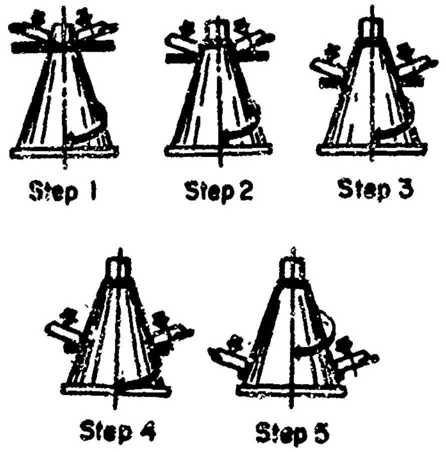


FIGURE 3-24.0-1. STEPS IN SHEAR FORMING OF A CONE[2]

3-24.1 EQUIPMENT SETUP AND TOOLING

Most engine-lathe manufacturers will make equipment for spinning.

The latest equipment incorporates numerical control for automatic programming of the spinning operation.

Shear-forming machines are an extension of the capabilities of the spinning lathe. The machines are heavier and have considerably more power than the spinning lathes. Spinning can, however, be conducted on a shear-forming machine capable of producing cones.

Shear-forming machines are available in a variety of sizes, as indicated in Table 3-24.1-1. Additional sizes of machines may be available, so that the manufacturers should be informed of specific requirements. One of the largest shear-forming machines can handle a blank 240 inches in diameter.[5]

TABLE 3-24.1-1. TYPICAL AVAILABLE SPINNING AND SHEAR-FORMING MACHINE SIZES[2,3,4]

Manufacturer	Part Diameter, in.	Part Length, in.	Production Rate, piece/hr
Lodge & Shipley	12	15	75-100
(Floturn)	12	15	90-125
	24	30	30-80
	40	50	8-30
	60	70	1-15
	70	84	1-15
Cincinnati Milling	42	50	--
Machine Company	42	50	--
(Hydrospin)	62	50	--
	70	72	--
Hufford (Spin	60	60	--
Forge)	60	120	--

Planishers for manual spinning are generally made of relatively soft material, such as brass, to prevent gouging of the workpiece. For mechanical or hydraulic spinning, rollers of hardened tool steel are used. A high-speed tool is required when elevated-temperature spinning is performed. The surface of the rollers is often chromium plated for durability and corrosion resistance. The diameter of the rollers in spinning is selected on the basis of the diameter of the part to be formed; the roller diameter should be approximately half the smallest diameter of the part.

Mandrels for room-temperature spinning can be made of wood or plastic for production runs of 25 parts or less. For greater production, the mandrels may be made of ductile cast iron or tool steel. For elevated-temperature spinning the mandrels are made of ductile cast iron or high-speed tool steels. For short-run production of titanium, a wood form covered with aluminum and steel has been used at temperatures to 1300 F.[6] This mandrel is shown in Figure 3-24.1-1.

Shear forming requires stronger tooling than spinning because of the greater forces characteristic of the process. Rollers are used for applying the forming force to the blank. The diameter of the rolls is generally kept to a minimum consistent with the force it is required to transmit. A smaller roller has less contact area with the blank and consequently less friction and power loss. The shape of the roller depends on the amount of reduction to be taken with each pass. A typical roller configuration is shown in Figure 3-24.1-2, and the surfaces, which are important in the process, are indicated. The contact angle determines the length of contact surface for any given reduction. The greater the contact length the greater the frictional forces between the roller and the metal. The approach surface and contact angle are required to prevent the material from burring ahead of the roller. Since the roller step controls the amount of reduction, a different roller is required for each reduction. The burnishing angle and land tend to smooth out the ring marks left on the part due to the axial travel of the tool. Rollers for shear forming are generally made of high-speed tool steel heat treated to R_C 60. The surface is polished and sometimes chromium plated for use at either room temperature or elevated temperature.

The rollers in shear forming are generally cooled to prevent distortion or creep under heavy loads. This is usually accomplished by spraying a lubricant on the roller surface; internal circulating cooling systems are not very practical.

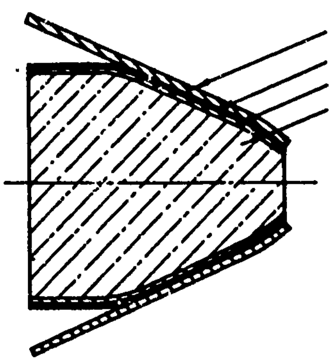


FIGURE 3-24.1-1. ELEVATED-TEMPERATURE SPINNING OVER A WOOD MANDREL[6]

The mandrels for shear forming are made of heat-treated steel because of the high forces involved. A softer material would be locally deformed by the roller pressure. Large mandrels are generally made as shells with supporting internal structure, while smaller mandrels are solid.

3.24.2 BLANK PREPARATION

The requirements for edge preparation on titanium-alloy blanks are similar to most other materials. The edges should be smooth and free of notches or scratches. The surface of the blank should also be free of scratches. Any surface contamination should be removed before spinning or shear forming.

The most common lubricants used on titanium at elevated temperatures are the solid-film types such as graphite, molybdenum disulfide, and mica. Although they can be applied as a powder in most metal-forming operations, they should be suspended in a suitable vehicle for spinning or shear forming. Silicone oils, heavy petroleum-base drawing oils, and synthetics have been commonly used in other forming operations and might be considered for spinning.

Most grease-solid mixtures are compounded as relatively heavy greases that must be applied by swabbing. If used in spinning, a heavy build-up on the tools might be expected. A reduction in the viscosity of the grease should help if this occurs.

Specific lubricants that have been used on shear forming of titanium alloys are Esso's Nebula No. 2 and colloidal graphite in a petroleum-naphtha vehicle. These have been used at forming temperatures to 1300 F.[7,8]

Tests to evaluate the coefficient of friction of steel rubbing on titanium materials at room temperature have indicated that there is very little benefit from the use of lubricants.[9] The unlubricated surface had a coefficient of friction of 0.49. The most successful lubricants were the synthetic long-chain compounds like polyethylene glycol (0.26), polypropylene glycol (0.33) and sugar solutions, molasses (0.32), honey (0.32), and maple syrup (0.32). It is doubtful that any of these lubricants could be used at elevated temperatures.[9]

Spinning required the use of a circular blank with sufficient material to complete the part plus, generally, some allowance for trimming after forming. The radius for the blank can be determined by examining a section through the completed part and measuring the total length of material required to make the shape starting from the center of the part to one edge. The allowance for trim stock is added to this. The allowance for trimming should be a minimum of 1 inch. The maximum is dictated by the scrap allowed and the swing of the machine.

Cone shear forming requires a blank with the same diameter as that of the finished part. Some additional allowance for trim stock is desirable to reduce the possibility of cracking in the edge of the part, which is likely to occur when shear forming is carried to the end of the blank. The trim allowance should be at least equal to the

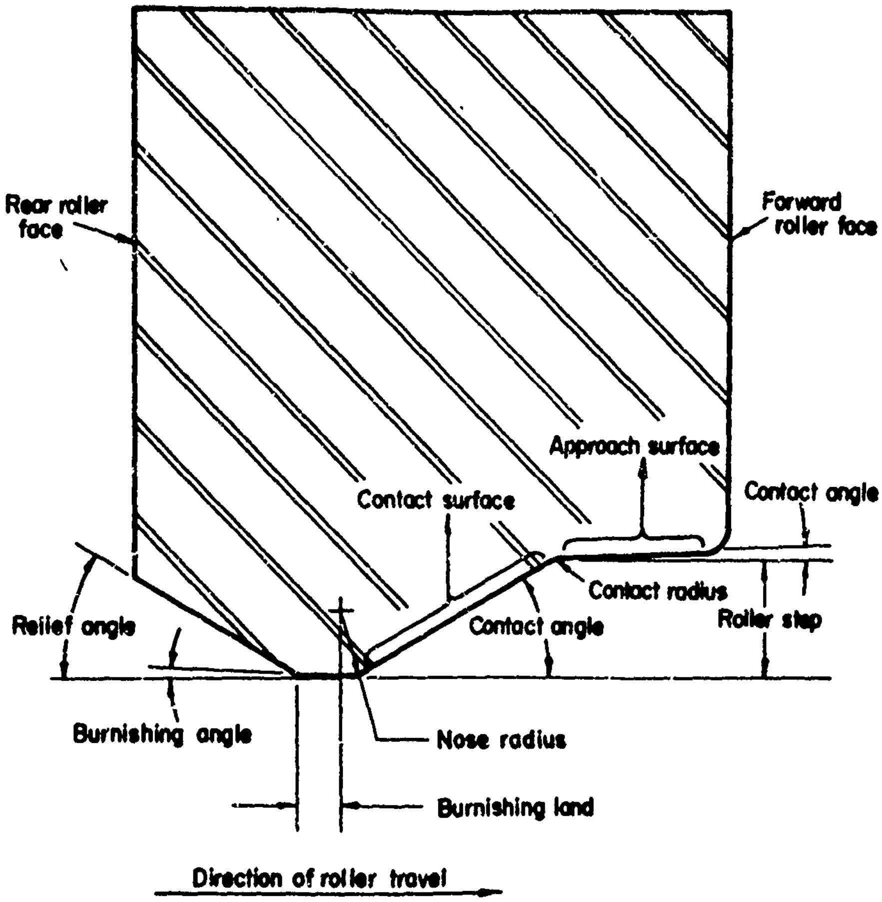


FIGURE 3-24.1-2. ROLLER CONFIGURATION FOR SHEAR FORMING(7)

original blank thickness. A greater allowance is controlled by the amount of trim scrap to be accepted.

Forward tube shear forming requires a blank with an inside diameter equal to the diameter of the finished part. The length of the tube blank is determined by the length of the finished part desired and the reduction to be accomplished. For a part shear formed to a 50 percent reduction, the length of the blank would be 1/2 of the finished part length. Some allowance for trim should be made in forward shear forming. An allowance of 1 inch for each 10 inches of finished length is normal practice.

Backward tube shear forming requires the same consideration in blank development as forward shear forming. The same reasoning is used in selection of the blank length. The blank inside diameter is the same as the finished-tube diameter.

3-24.3 BLANK HEATING METHODS

For elevated-temperature spinning or shear forming, the mandrels are generally heated. This can be accomplished by electric-resistance cartridges or by flames. The electric-resistance method may be more expensive to operate, but provides less opportunity for contamination of materials that tend to oxidize readily. The rotating contacts that transmit current to the mandrel sometimes limit the amount of power that can be used.

Flame heating of the mandrel can be accomplished with natural gas or bottled gas. With this practice, mandrels are generally hollow, so the flame can be played on the inside surface of the mandrel. Localized overheating must be avoided to prevent distortion of the mandrel.

The blanks are generally heated with a torch that applies heat locally to the area where the tooling force is applied. Very close control must be maintained to prevent overheating of the parts. The proper size of the torch depends on the thickness of material and the speed and feed rate of the operation. Blanks for spinning small parts or thick parts can be heated in a furnace and then transferred to a lathe for spinning. The limitations of this type of operation are determined by the time required for the spinning operation. Shear-forming operations generally take longer, so that only thick blanks permit using this

technique. Torch heating is the accepted practice for shear-forming sheet metal. The selection of the proper temperature for shear forming is also influenced by the temperature rise associated with deformation at the tool point.

Blanks can also be heated by radiation from resistance units located around the part. This technique works well on tubing or preforms that are to be shear formed, but is difficult to control when processing flat blanks.

3-24.4 SPINNING AND SHEAR FORMING LIMITS

During spinning, the metal blank is subjected to bending forces along the axis of spinning and compression forces tangential to the part. Difficulties are encountered with elastic buckling when the ratio of the depth of the spun part to the thickness of the metal becomes too great. Elastic buckling occurs in the unspun flange of the part.

The ratio of depth to diameter of parts that can be produced by spinning is limited by plastic buckling. This is related to the material properties in terms of the ratio of tensile modulus to the ultimate tensile strength.[10] Exceeding the formability limits causes shear splitting or circumferential splitting.

Typical spinning-limits curves are shown in Figures 3-24.4-1 and 3-24.4-2. Within the envelop, good parts can be made; failures will occur by plastic buckling if the height-to-radius ratio (H/R) becomes too large, and failure by elastic buckling will occur if the height-to-thickness (H/T) becomes too large. The position of the curves will vary according to the properties of the material and the forming temperature.

Table 3-24.4-1 gives some formability limits for manual spinning the Ti-6Al-4V and Ti-13V-11Cr-3Al alloys at room temperature. They are expected to hold for relatively small forces and limited amounts of thinning. The data show that spinnability is favored by smaller ratios of blank diameter to sheet thickness. Neither material will withstand very severe deformation at room temperature. For example, the limit for a 3-1/8-inch-diameter, 1/8-inch-thick blank of Ti-6Al-4V alloy appears to be a flat cup 2.6 inches in diameter and 0.365 inch high.

Figure 3-24.4-3 shows the effect of temperature on the parameter (compression modulus/compression yield strength) that controls elastic buckling. For both alloys, the change toward better formability starts around 1000 F and increases rapidly around 1400 F. The latter temperature is approximately the highest temperature that can be used without degrading the properties of the alloys. The total time required for forming

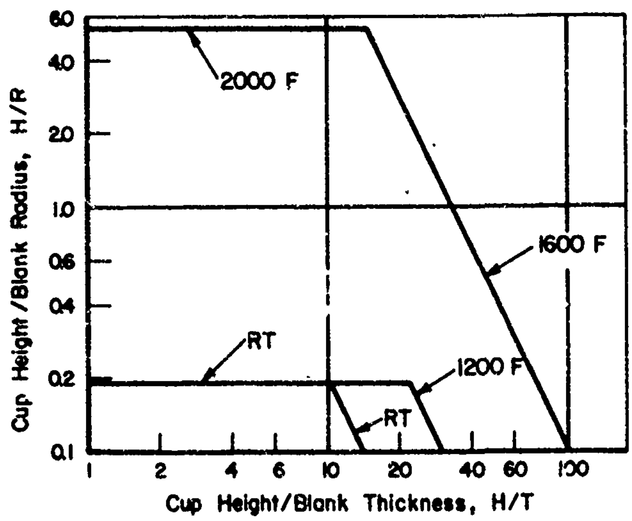


FIGURE 3-24.4-1. ANALYTICAL EXTENSION OF SPINNING-LIMIT CURVE FOR Ti-8Al-1Mo-1V ALLOY[11]

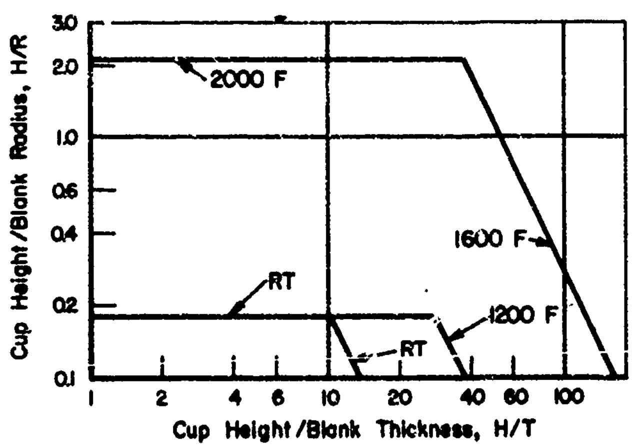


FIGURE 3-24.4-2. ANALYTICAL EXTENSION OF SPINNING-LIMIT CURVE FOR Ti-13V-11Cr-3Al ALLOY[11]

may also influence the choice of spinning temperature.

Based on very few data, it is believed that the parameter controlling plastic buckling (elastic modulus/ultimate strength) does not change in titanium alloys at temperatures below 1000 F.

Commercially pure and alloy titanium have been shear formed at room temperature and at elevated temperature. For reductions greater than 15 percent for cones and 50 percent for cylindrical sections, elevated temperatures are desirable. In shear forming of titanium, the ratio between the strength of the material being formed and the applied shear-forming stresses is critical. The strength of titanium changes significantly with

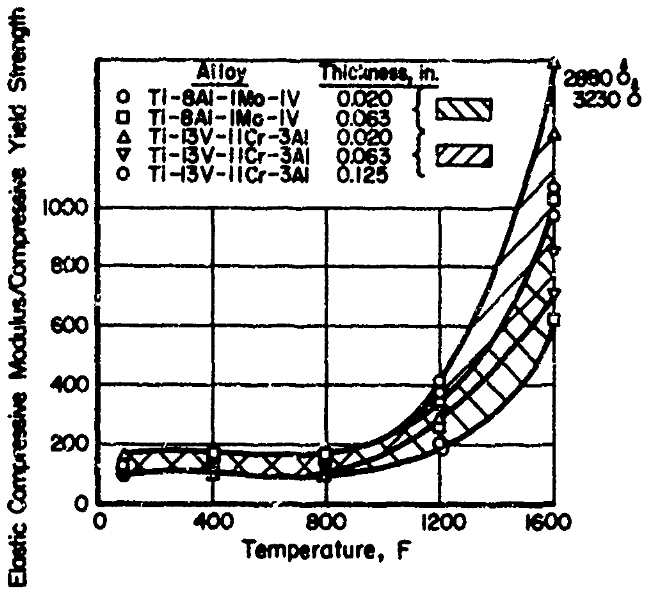


FIGURE 3-24.4-3. EFFECT OF TEMPERATURE ON ELASTIC-BUCKLING LIMIT IN SPINNING[11]

TABLE 3-24.4-1. FORMABILITY LIMITS FOR MANUAL SPINNING OF FLAT-BOTTOM CYLINDRICAL CUPS AT ROOM TEMPERATURE[10]

		Limiting Ratio for Alloys Indicated[a]			
		Blank Diameter/ Cup Diameter		Cup Height/ Cup Diameter	
Thickness, inch	Blank Diameter/ Sheet Thickness	AMS 4911	AMS 4917	AMS 4911	AMS 4917
0.020	25	1.3	1.2	0.22	0.14
	50	1.3	1.2	0.22	0.14
	100	1.2	1.2	0.14	0.14
	150	1.2	1.1	0.14	0.07
	200	1.1	--	0.07	--
0.063	25	1.3	1.2	0.22	0.14
	50	1.2	1.2	0.14	0.14
0.125	25	1.2	1.2	0.14	0.14
	50	1.1	--	0.07	--

(a) Alloys AMS 4911 and AMS 4917 contain, respectively, Ti-6Al-4V and Ti-13V-11Cr-3Al.

The term cup diameter refers to the inside diameter; the cup height is based on the outside dimension.

relatively small changes in temperature within the elevated-temperature working range, so that it is necessary to control the temperature within 35 F or less.

Elevated-temperature shear-forming operations have been conducted at temperatures from 400 to 1600 F, depending on the alloy being formed. Typical forming temperatures for several alloys are given as follows:[8,12,13]

Material	Shear-Forming Temperature, F
Commercially pure	800 to 1000
Ti-5Al-2.5Sn	1200 to 1400
Ti-6Al-4V	1100 to 1200
Ti-13V-11Cr-3Al	1600 to 1800

The percentage reduction of material thickness during cone shear forming is a function of the part shape and is related by the "sine law". Figure 3-24.4-4 shows the geometric measurements that are important for shear forming a cone. The sine law states that the final thickness is related to the initial thickness of the blank by the sine of the half angle of the cone:

$$T = T_b \times \sin a/2 ,$$

where

T = the final thickness, inches

T_b = the initial blank thickness, inches

a = the included angle of the cone, degrees.

The percentage reduction is therefore related to the sine of the half angle of the cone as follows:

$$R = 100\ (1 - \sin a/2) ,$$

where

R = the percentage reduction.

The sine law also applies to shapes other than a cone, with the final thickness at any given point along the part being determined by the angle the part makes with the axis at that point. The forming of a hemisphere would consequently result in a variation of thickness, with the bottom of the hemisphere the same thickness as the blank and the edge being the thinnest section. The limiting reductions will depend on the ductility of the material at the forming temperature. Typical reductions for cone forming of annealed titanium alloys are given in Table 3-24.4-2.

As shown in Figure 3-24.4-5, shear forming of tubes can be of two basic types: forward and backward. In forward tube shear forming, the material flows in the same direction as the tool motion, usually toward the headstock. In backward shear forming, the material flow is opposite to the roller travel--usually toward the tailstock.

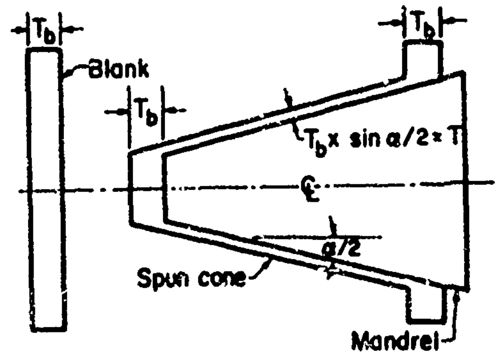


FIGURE 3-24.4-4. GEOMETRIC RELATIONS IN CONE SHEAR FORMING[14]

TABLE 3-24.4-2. REDUCTIONS IN SHEAR-FORMED CONES[15]

Formed at Room Temperature

Alloy	Number of Passes	Total Reduction, percent
Ti-4Al-3Mo-1V	1	60
Ti-6Al-6V-2Sn	1	40
Ti-6Al-4V	3	80
Ti-13V-11Cr-3Al	4	58

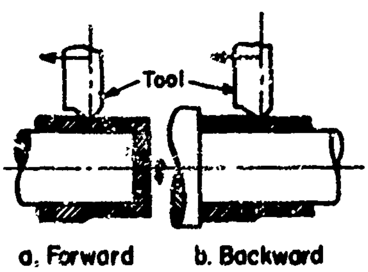


FIGURE 3-24.4-5. SCHEMATIC OF TUBE SHEAR FORMING[16]

In shear forming of tubing, the basic sine law of shear forming cannot be applied. The maximum permissible reduction for ductile materials depends on the state of stress in the deforming area and the material properties. The maximum reduction can be predicted from the tensile reduction in area both for cone and tube shear forming[17]. The experimental data shown in Figure 3-24.4-6 indicate that a maximum shear-forming reduction of about 80 percent requires a tensile reduction in area value of 50 percent. Beyond this tensile reduction value,

there is no further increase in formability. Materials with a reduction in area less than 50 percent require consideration of their ductility to determine formability.

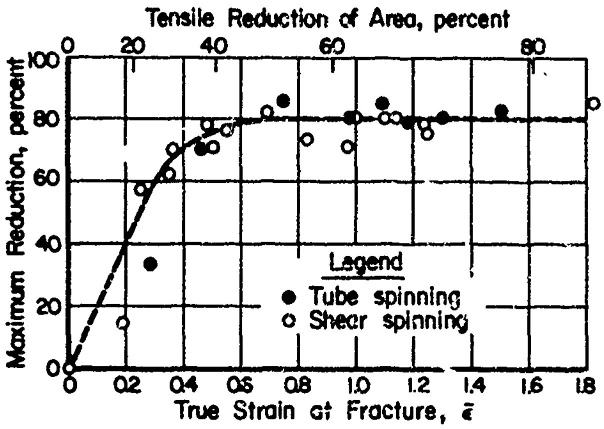


FIGURE 3-24.4-6. MAXIMUM SHEAR-FORMING REDUCTION IN TUBES OF VARIOUS MATERIALS AS A FUNCTION OF TENSILE REDUCTION IN AREA(17)

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3-25 Dimpling

3-25.0 INTRODUCTION

Dimpling is a process for producing a small conical flange around a hole in sheet-metal parts that are to be assembled with flush- or flat-headed fasteners. The process is often used for preparing fastener holes in airframe components because the flush surface reduces air drag. Dimpling is most commonly applied to sheets that are too thin for countersinking. Since drilled holes have smoother edges than punched holes, they are more suitable for dimpling. Sheets are always dimpled in the condition in which they are to be used because subsequent heat treatment may cause distortion and misalignment of the holes.

The ram-coining-dimpling process is most common, although dimples have been produced at room temperature by swaging. In this process, pressure in excess of that required for forming is applied to coin the dimpled area and reduce the amount of springback.

3-25.1 EQUIPMENT SETUP AND TOOLING

The choice of the size of ram-coining-dimpling equipment depends on the pressures needed to deform the sheet. A guide in choosing size ranges for dimpling machines needed to produce dimples for various rivet and screw sizes is given below.[1]

Size	Dimpling-Pressure Capacity, lb
3/32- to 1/8-inch rivets	Up to 10,000
5/32-inch rivet	10,000 - 20,000
3/16-inch rivet and screw	15,000 - 25,000
1/4-inch rivet and screw	18,000 - 40,000
5/16-inch screw	25,000 and up

The actual pressures vary according to the sheet thickness being dimpled. The limits of a 20,000-pound-capacity dimpler for various thicknesses of sheet are shown in Table 3-25.1-1. Dimpling sheet thicknesses above the maximum given for each fastener size will require a change in punch and die geometry as well as an increase in the diameter of the pilot hole.

A typical sequence of operations for dimpling is shown in Figure 3-25.1-1. The five positions shown for a triple-action ram-coin dimpling machine are the approach, preform, coining, end of stroke, and retraction.

Titanium alloys must be dimpled at elevated temperatures. The practical optimum-temperature limit is 1200 F, which is about the highest temperature at which tool steels may be used as die materials. If dimpling must be done at higher temperatures, the use of high-strength, high-temperature alloys or ceramic tooling materials is required to prevent deformation of the die materials during dimpling.

Elevated-temperature dimpling is usually done with heated dies, the sheet to be dimpled being heated by contact with the dies, as shown in Figure 3-25.1-1. Conduction-heated, ram-coin tooling may be used for temperatures up to 1000 F. Resistance-heated-dimpling equipment is used for higher temperatures. The tooling consists of a solid die and a two-piece punch assembly. The die is made of high-temperature-resistant steel. The punch cone is a composite of Kentanium and steel base. The pad is a special, high-alumina composition. The strap heaters were used to heat the punch pad and die, to reduce heat-sink effects, and to eliminate thermal shock on the pad. The dies may also be heated by induction, and such systems have been produced by one or more suppliers of dimpling dies.

One fabricator described a triple-action machine that has a maximum die temperature of 1000 F and a constant forming rate, and a second machine, of the double-action design, in which the dies may be heated to 800 F.[3]

TABLE 3-25.1-1. LIMITS OF DIMPLING TITANIUM SHEET FOR AN426-TYPE RIVETS ON A 20,000-POUND-CAPACITY MACHINE[a][1]

Fastener Designation	Diameter, inch	Sheet Thickness, inch: Unalloyed Titanium	Sheet Thickness, inch: Ti-8Mn Alloy
AN426-3	3/32	0.016 - 0.063[b]	0.025 - 0.063
-4	1/8	0.016 - 0.063	0.025 - 0.071
-5	5/32	0.020 - 0.063	0.025 - 0.071
-6	3/16	0.020 - 0.063	0.025 - 0.071
-8	1/4	0.025 - 0.063	0.025 - 0.071

(a) Thicker sheet must be dimpled with equipment having a larger capacity.
(b) Dimpled using 20,000-pound-capacity machine, Model CP450EA, Chicago Pneumatic Tool Company.

3-25.2 MATERIAL PREPARATION

As for other bending operations with titanium and its alloys, factors that permit maximum formability are consistent yield strengths from sheet to sheet, minimum thickness and flatness variations between sheets, and high-quality surface finishes.[4]

The quality of the drilled pilot hole has an important influence on the success of dimpling.

3-25:67-2

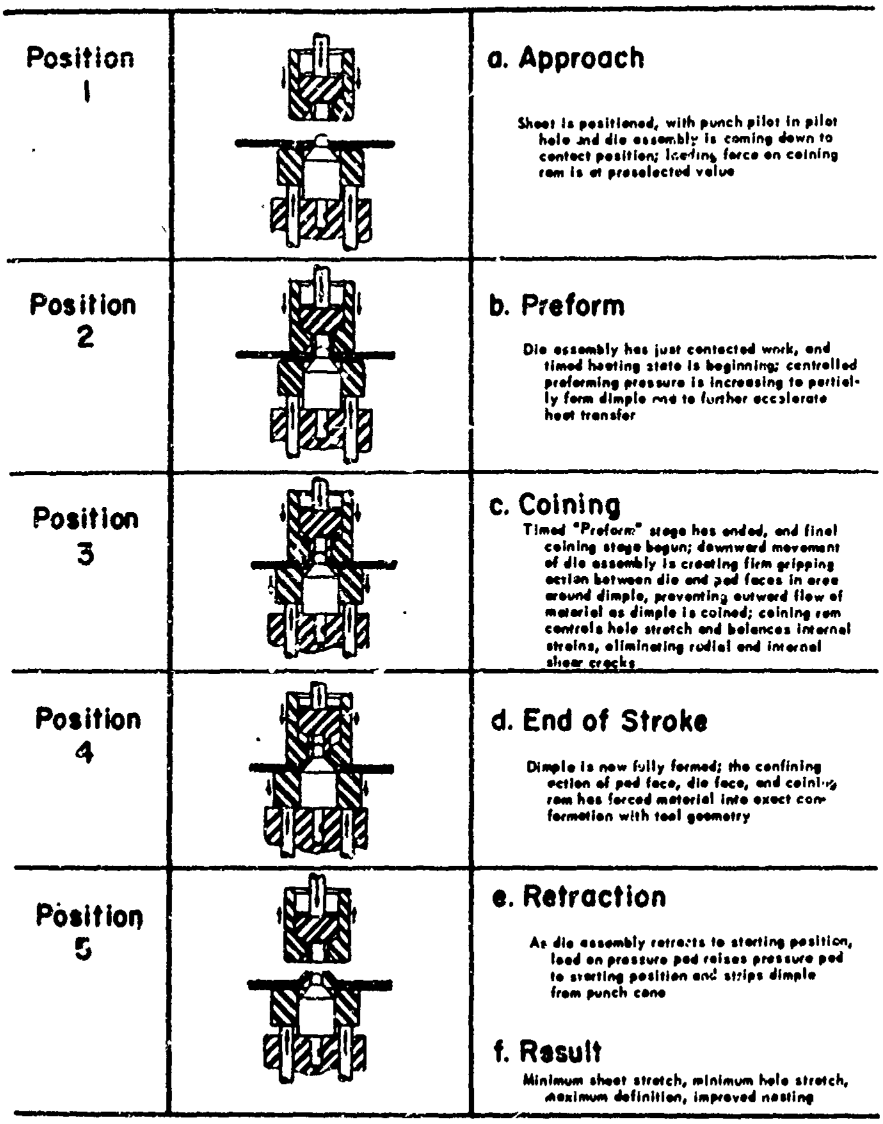

FIGURE 3-25.1-1. SEQUENCE OF OPERATIONS IN TRIPLE-ACTION RAM-COIN DIMPLING[2]

The holes must be smooth, round and cylindrical, and free of burrs. Hand drilling is not recommended. Burrs or wire edges remaining around the holes may be detached during dimpling and lodge on ' punch or die.

Pilot-hole sizes should conform to specifications applicable to aluminum alloys. The pilot holes should be drilled with stub drills designed for titanium that conform to the Aircraft Industries Association drill purchasing specification. Such drills produce holes with straight sides that are satisfactory for dimpling.

Care must be taken in deburring holes for dimpling. Because of the notch sensitivity of titanium, only the material turned up by the drill at the edges of the hole should be touched and removed. Hand deburring with a countersink cutter has proven satisfactory. Power-driven countersinks that chatter are not satisfactory since chatter marks are potential sources of radial cracks.

A power-driven deburring tool has been used successfully in production with titanium. The tool is mounted in the chuck of a 1000-rpm pneumatic-drill motor, and a microstop is adjusted to cut the burr flush with the sheet surface. Such a machine produces a satisfactory deburr and leaves a smooth hole edge.

Dimpling at both room and elevated temperatures with titanium and its alloys is accomplished without lubricants.

3-25.3 DIMPLING LIMITS

As would be expected in a press-die-forming operation of this kind, the permissible deformation depends on the ductility of the titanium. The amount of stretching required to form a dimple varies with the head diameter, D, of the fastener, the rivet diameter, 2R, and the bend angle, α. The parameters for a dimple are shown in Figure 3-25.3-1. If the ductility of the material is

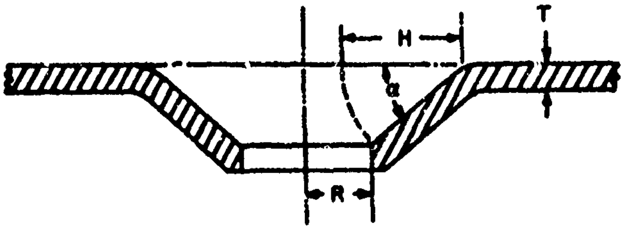

FIGURE 3-25.3-1. PAPAMETERS FOR DIMPLING[5]

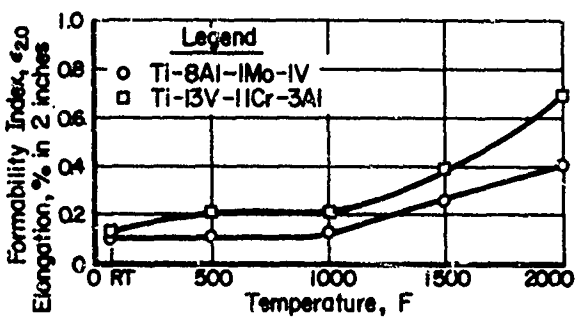

FIGURE 3-25.3-2. RELATIONSHIP BETWEEN ELONGATION AND TEST TEMPERATURE AS DETERMINED IN TENSILE TEST[6]

insufficient to withstand forming to the intended shape, cracks will occur radially in the edge of the stretch flange or circumferentially at the bend radius. The latter type of failure is more prevalent in thinner sheet. Radial cracks are more common in thick stock.

Figure 3-25.3-2 shows the relationship between elongation and temperature for the Ti-8Al-1Mo-1V and the Ti-13V-11Cr-3Al alloys. Temperatures above 1200 F must be used for dimpling both alloys.

Figure 3-25.3-3 shows the theoretical relationship between the H/R ratio and the bend angle, α, for the Ti-13V-11Cr-3Al and the Ti-8Al-1Mo-1V alloys at room temperature, 1200 F, and 2000 F. The Ti-13V-11Cr-3Al alloy can be more readily formed at all three temperatures than the Ti-8Al-1Mo-1V alloy. Good parts can be formed for conditions under the curves, while split parts can be expected for conditions above the curves. The major failure in dimpling is caused by simple tension.[6]

Table 3-25.3-1 gives dimpling limits for radial splitting at the edge of the hole for two

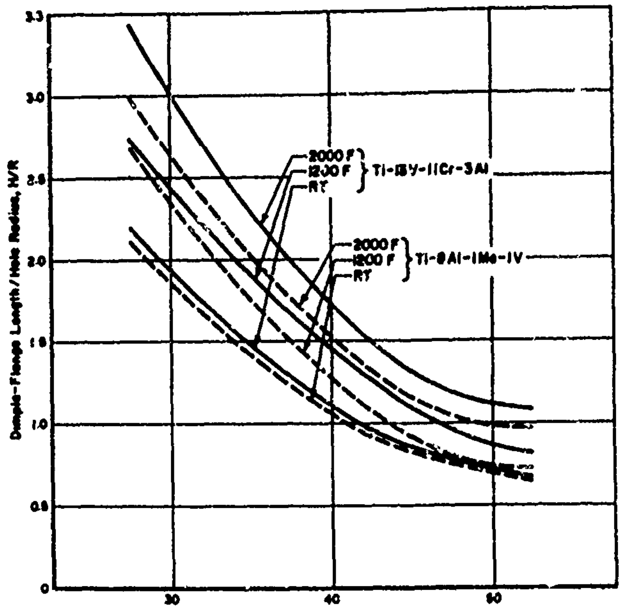

FIGURE 3-25.3-3. THEORETICAL RELATIONSHIP BETWEEN RATIO H/R AND BEND ANGLE FOR THE DIMPLING OF TWO TITANIUM ALLOYS[6]

titanium alloys dimpled at room temperature. Bend angles above and below the standard 40-degree angle are given. Other conditions of heat treatment and dimpling at elevated temperatures would necessitate the use of other dimpling limits.

The temperatures in Table 3-25.3-2 are suggested for dimpling commercially pure titanium sheet and for several titanium alloys. Dimpling, under certain conditions, can be done at somewhat lower temperatures, but the springback will be greater and more erratic, higher forming pressures will be needed, and the possibility of failure by cracking is greatly increased.

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TABLE 3-25.3-1 DIMPLING LIMITS(6,7)

Radial Splitting at Edge of Hole

Material	Condition	Dimpling Temperature, F	Dimpling Limits, H/R For Various Bend Angles, α, Above and Below Standard Bend Angle				
			30°	35°	40° (Standard)	45°	50°
Ti-6Al-4V	Mill annealed	RT	2.00	1.5	1.17	0.92	0.74
Ti-13V-11Cr-3Al	Aged 900 F	RT	1.58	1.17	0.91	0.73	0.60
Ti-8Al-1Mo-1V	Duplex annealed	RT	1.83	1.42	1.08	0.82	0.70
Ti-13V-11Cr-3Al	Solution annealed	1200	2.58	1.95	1.48	1.15	0.96
Ti-8Al-1Mo-1V	Duplex annealed	1200	2.30	1.72	1.30	1.00	0.85

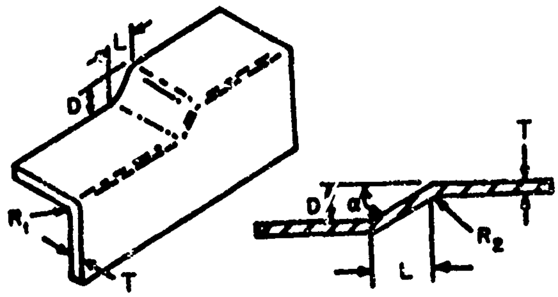
TABLE 3-25.3-2. SUGGESTED TEMPERATURES FOR HOT DIMPLING OF TITANIUM AND ITS ALLOYS(8)

Alloy	Condition	Temperature, F	Remarks
Commercially		500-600	
Ti-8Mn		725-775	0.025 to 0.091-inch-thick sheet
Ti-8Al-1Mo-1V		750	0.022 to 0.063-inch-thick sheet
Ti-6Al-4V	Mill annealed	900	
		1300-1350	
Ti-5Al-2.5Sn		1600-1800	
Ti-4Al-3Mo-1V	Annealed (ST)	>1000	
	Aged (STA)	>1000	Special tooling required; maximum thickness, 0.045 inch
Ti-4Al-3Mo-1V	Aged	1300-1350	Zephyr process
Ti-2Al-6Mo-2V		1200-1250	
Ti-2.5Al-16V		600-800	
Ti-13V-11Cr-3Al	Aged, 900 F	900	
Ti-5Al-2.75Cr-1.25Fe	Solution heat treated	600	
	Aged	1200	
Ti-13V-11Cr-3Al	Solution heat treated	600	

3-26 Joggling

3-26.0 INTRODUCTION

A joggle is an offset in a flat plane produced by two parallel bends, in opposite directions, at the same angle. Joggling permits flush connections to be made between sheets, plates, or structural sections. The bend angle for joggles is usually less than 45 degrees, as indicated in Figure 3-26.0-1. Because the bends are close together, the same flange will contain shrunk and stretched regions in close proximity to each other. The two types of deformation tend to compensate for each other.



α = joggle-bend angle
D = joggle depth
L = joggle length or runout
T = thickness of workpiece
R_1 = radius on joggling block
R_2 = radius of bend on leading edge of joggle block.

FIGURE 3-26.0-1. JOGGLE IN AN ANGLE[1]

3-26.1 EQUIPMENT SETUP AND TOOLING

Joggles may be formed either in straight or curved sheet-metal titanium sections by a variety of techniques. Drop hammers or power brakes with special joggle dies and presses are often employed. Hydraulic presses are preferred for joggling at elevated temperatures because they simplify control of pressure and dwell time. The joggles usually are formed either by a wiping action or a section movement.

Joggling of titanium often is done at elevated temperatures. Tool steels are limited to service temperatures below approximately 1200 F. For higher temperatures, tooling constructed from high-strength, heat-resistant alloys or ceramic materials must be used.

Figure 3-26.1-1 is a sketch of a hot joggle die used in preliminary studies to establish joggle parameters.[2] The joggle pad holder is made from hot-rolled steel. The Meehanite joggle pads (four in number) have four electric cartridge heaters. The pads have varying radii to accomdate different thicknesses of metal. The die set can be used for temperature up to 1400 F and is controlled by a thermocouple to ±25 F.

A schematic drawing of a "universal joggle die is shown in Figure 3-26.1-2. This type of tooling requires an additional hydraulic cylinder to apply horizontal forces to clamp the side of the angle specimen to the die.

3-26.2 MATERIAL PREPARATION

Surface imperfections such as scratches and file marks must be avoided. Blanks for joggling should be protected by interleaving with paper or cardboard to minimize scratching of the sheet surfaces during handling.

Lubricants are generally used in the production joggling of titanium sheet metal. Tests have been performed, however, at temperatures ranging from that of the room to 1125 F without the use of lubrication.[3] Lubricants containing flake or powdered graphite have been used for joggling at 850 F. One such commerical product is Dag-41, which was used successfully for joggling the Ti-8Mn alloy at 850 F.[4] Lubricants containing molybdenum disulfide also are used for joggling and other metal-forming operations, especially those performed at elevated temperatures. Mineral oil and other oil bas s containing various additiv s are used at room temperature.

3-26.3 BLANK-HEATING METHODS

Four methods are used for heating dies and/or sheet stock for joggling.[5] They are integrally heated dies, radiant heating, resistance heating, and gas-torch heating. Gas-torch heating is a good, inexpensive way to heat dies to the forming temperature, but is not recommended for blank heating. Rather than preheating them, thin workpieces are often heated by contact with hot tools.

The use of cartridge-type heaters for the heating of joggle dies was illustrated in Figure 3-26.1-1. The self-contained cartridge-type heaters are inserted into the joggle-die set. Close temperature control is possible with this heating method. Sometimes both the sheet and the dies are heated by radiation; quartz lamps have been used for this purpose.

3-26.4 JOGGLING LIMITS

Relationships can be established between the properties of the workpiece and the formability limits in joggling. The common types of failures in joggling are buckling and splitting. The terms D, L, and T defining the geometry of the joggle were illustrated in Figure 3-26.0-1. The mechanical properties of the workpiece needed to determine joggle formability are:

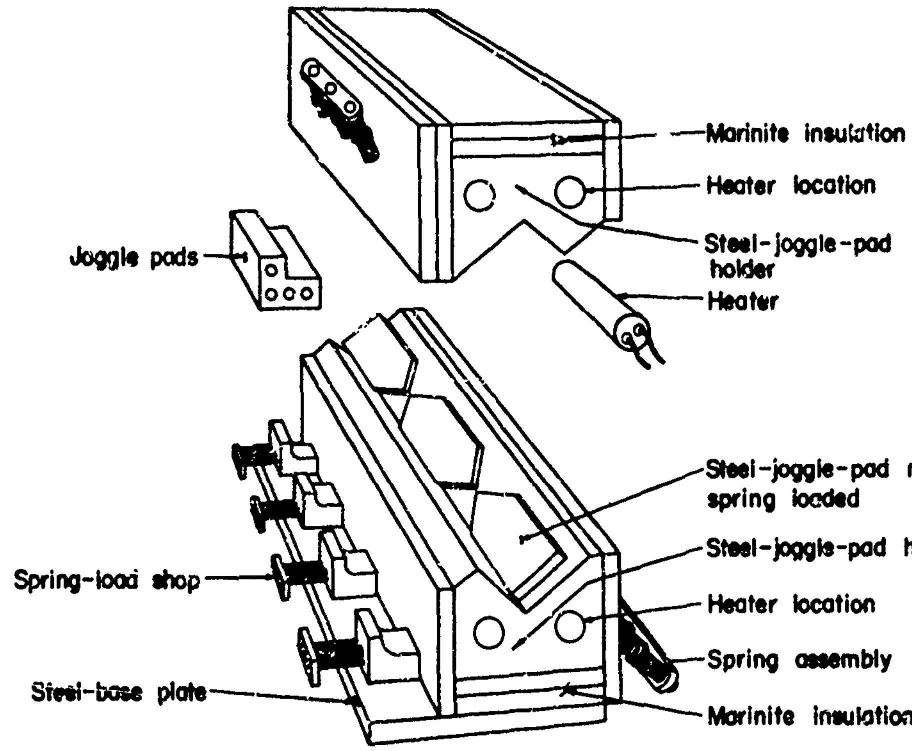


FIGURE 3-26.1-1. JOGGLE-DIE SET DESIGNED TO OPERATE UP TO 1400 F (2)

E = Young's modulus of elasticity

S_{cy} = yield strength in compression based on the original cross-sectional area

$\epsilon_{0.02}$ = conventional strain to rupture measured on a 0.02-inch gage length.

Although values of $\epsilon_{0.02}$ are not commonly reported, they can be determined by special tests. If the mechanical properties are known, joggling-limit curves can be constructed. Limits determined in that way for the Ti-13V-11Cr-3Al alloy are given in Table 3-26.4-1. The data are for joggling under conditions where $R_1 = 6T$, and $R_2 = 0.032$ inch.

Another empirical approach may be used to choose joggle dimensions.(6) The length or runout, L, of the joggle can be determined from the following formulas and the factors A, B, and C given in Table 3-26.4-2.

(1) If the joggle depth is greater than A, the length of the joggle runout equals B times the joggle depth or L = BD (when D > A).

(2) If the joggle depth is less than A, the length of the joggle runout is equal to the square root of the joggle depth times the quantity C minus the joggle depth, or

$$L = \sqrt{D(C - D)} \quad \text{(when } D < A\text{)}.$$

TABLE 3-26.4-1. JOGGLING LIMITS FOR SOLUTION-TREATED Ti-13V-11Cr-3Al ALLOY(1)

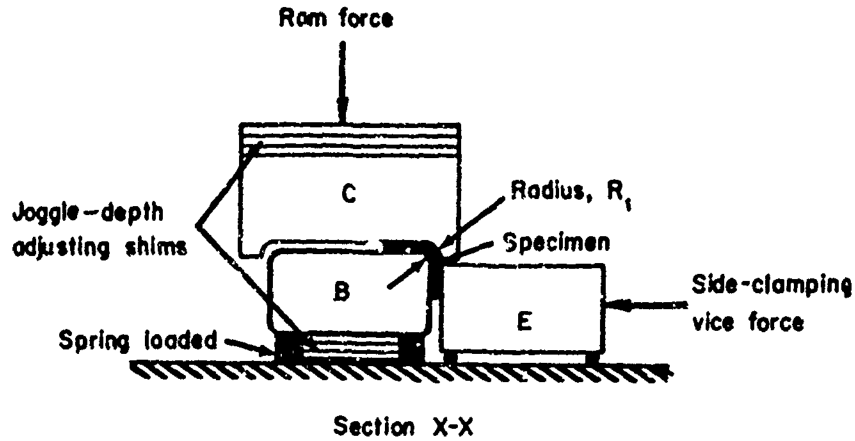
	D/L	Buckling Limit for D/L Indicated(a), D/T	Corresponding Ratio, L/T
	0.05	3.55	71
	0.10	2.50	25
	0.20	1.76	9
	0.30	1.45	5
	0.50	1.15	2.3
Splitting limit	0.80		
Critical ratio			1.44

(a) These limits appear to be based on the performance expected for a material with an E/S_{cy} ratio of 208 and an $\epsilon_{0.02}$ value of 0.23.

(3) For joggles in flat sheets, the projected distance between tangents may be determined from the equation for reverse curve as follows:

$$L = \sqrt{D(4R_2 + 2T - D)} \quad \text{(see Figure 3-26.0-1).}$$

Additional data for four alloys are summarized in Table 3-26.4-3. Springback of the



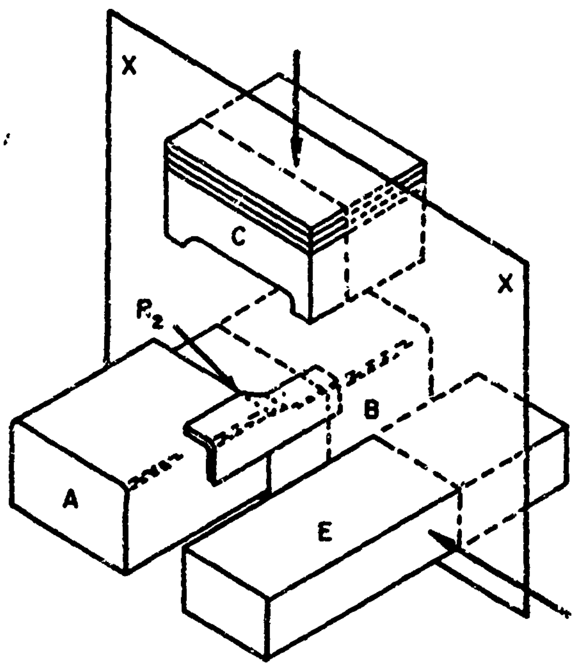


FIGURE 3-26.1-2. SCHEMATIC OF JOGGLE DIES[1]

Ti-2.5Al-16V alloy at the minimum joggle length was 10 to 15 percent greater than that of the Ti-4Al-3Mo-1V alloy. The minimum joggle length of the alloy is roughly half that determined for the Ti-4Al-3Mo-1V and the Ti-2.5Al-16V alloys for sheet up to about 0.063 inch in thickness. For 0.090-inch-thick sheet, the minimum radii are very nearly equal.

Figure 3-26.4-1 is a composite of joggle data on three titanium alloys in which joggle depth is plotted against joggle length.

3-26.5 <u>SELECTED REFERENCES ON JOGGLING</u>

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(4) "Notes on Hot Forming of Ti-8Mn Sheet", Memorandum from Titanium Metallurgical Laboratory, Battelle Memorial Institute, Columbus, Ohio (April 20, 1956).

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(7) Carpenter, S. R., Woodward, R. D., Alesch, C. W., and Green, E. D., "Titanium Development Study Program", Final Report, Contract No. AF 33(600)-34876, Convair Division, General Dynamics Corporation, San Diego, California.

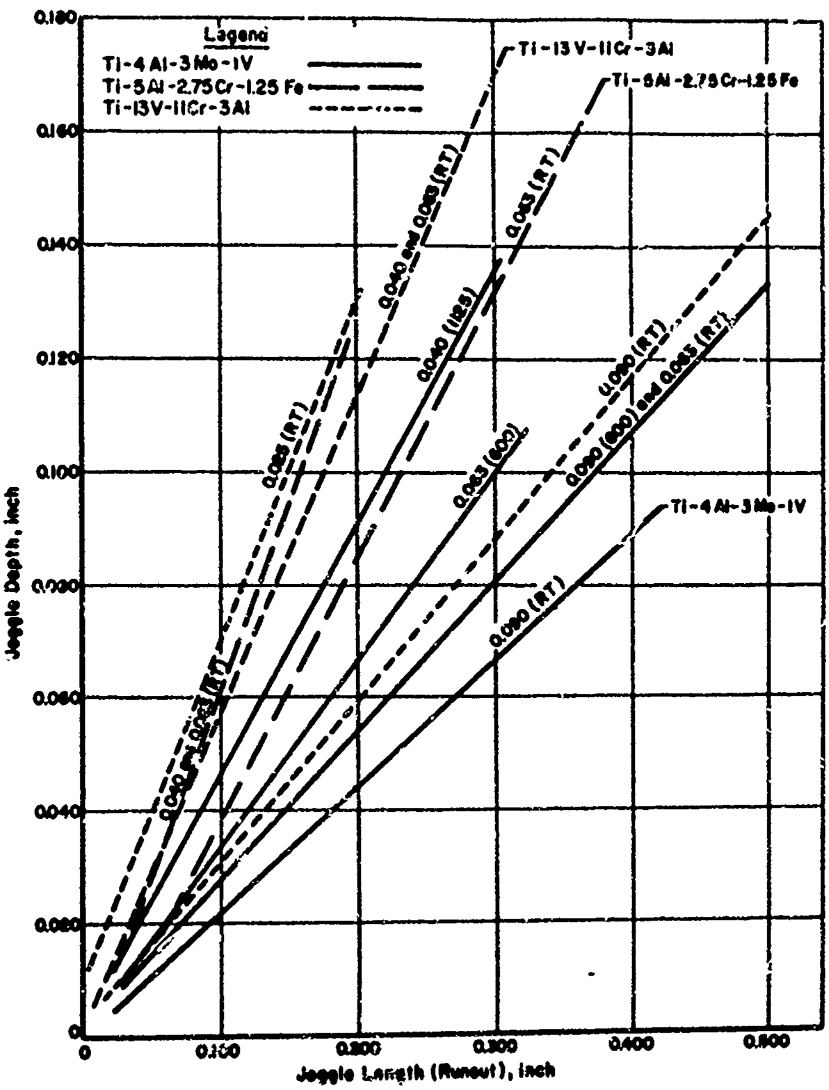


FIGURE 3-26.4-1. JOGGLE RELATIONSHIPS FOR THREE SOLUTION-TREATED TITANIUM ALLOYS(2)

TABLE 3-26.4-2. FACTORS FOR ROOM-TEMPERATURE JOGGLING OF TITANIUM ALLOYS(6)

Alloy Thickness[a], inch	Factors for Minimum Bend Radii, R/T[b]	Factors for Minimum Joggle Runout — Joggle Factors[c] A/T	B	C/T
Commercially pure titanium				
Through 0.070	3	0.54	5	14
Over 0.070	3-1/2	0.62	5	16
4Al-3Mo-1V condition ST				
Through 0.080	5-1/2	2.4	3	24
Over 0.080	6	3.6	3	26
5Al-2.5Sn				
Through 0.080	5-1/2	0.92	5	24
Over 0.080	6	1.00	5	26
6Al-4V condition ST	7	0.81	6	30
8 Mn				
Through 0.080	4	0.69	5	18
Over 0.080	5	0.85	5	22
13V-11Cr-3Al				
Condition ST	3	1.4	3	14

(a) Condition ST is the solution-treated condition.
(b) To obtain the bend radii, multiply R/T value in the table by material thickness, T.
(c) To obtain A and C, multiply A/T and C/T values by material thickness, T.

TABLE 3-26.4-3. SUMMARY OF DATA ON JOGGLING FOUR SOLUTION-TREATED TITANIUM ALLOYS(2, 7)

Alloy	Sheet Thickness, T, in.	Temperature, F	Minimum Joggle Length[a], L, in.	Springback at Minimum Joggle Ratio, percent
Ti-4Al-3Mo-1V	0.040	--	--	35
	0.063	RT	3.5D	35
	0.090	"	4.25D	~50
	0.063	600	3.0D	--
	0.090	600	3.5D	--
Ti-2.5Al-16V	0.040	RT	--	~45-50
	0.063	"	3.5D	~45-50
	0.090	"	4.25D	~60-65
Ti-13V-11Cr-3Al	0.025	RT	1.5D	13
	0.040	"	1.7D	32
	0.063	"	1.7D	40
	0.090	"	3.4D	50
Ti-5Al-2.75Cr-1.25Fe	0.025	RT	--	32.5
	0.040	"	--	46.0
	0.063	"	--	46.5

(a) D = depth of joggle.

3-27 Hot Sizing

3-27.0 INTRODUCTION

Hot sizing utilizes the creep-forming principle to produce accurate formed parts by the controlled application of pressure, temperature, and time. Horizontal and vertical pressures, usually applied by presses, force irregularly shaped parts to assume their correct shape against a heated die. The pressure is normally applied in a vertical direction, the horizontal force results from reaction with rogid tooling. The pressures used should be the minimum required for the part, gage, and alloy. Forces which approach the yield strength of the material at the forming temperature are required. For titanium alloys, a temperature of 950 F or above is usually used. The forming takes place because the creep strength of the material has been lowered below the level of the applied stress.

The time required for forming varies with the alloy, gage of material, and the temperature of the tooling. Most operations take between 10 and 30 minutes to completely form a part. The parts are removed from the die and allowed to cool in still air after forming. The parts retain the room-temperature shape of the die against which they were formed, with suitable allowances for thermal expansion and the differential in thermal expansion between the part and the tool material.

3-27.1 EQUIPMENT SETUP AND TOOLING

In the selection of tooling materials for hot sizing, the effect of cycling the tools from room temperature up to 1500 F must be considered. Most tool steels will lose their strengths at this level, and the application may justify the consideration of superalloys. Tooling material that softens or distorts in service is of little use in sizing operations.

Hot-rolled steel can be used for short production lots, up to about 50 pieces, provided the sizing temperature does not exceed 1000 F.

Quality-controlled, high-silicon cast-iron (Meehanite) dies can be used for medium-run parts up to 100 pieces at temperatures to 1100 F. Scaling of this material restricts its use at higher temperatures. Wire brushing at intervals of 35 to 50 parts and light sand blasting of the die surface after 100 parts have been formed, prevents contamination of the titanium parts during hot sizing.

Greater quantities of parts can be obtained from tooling made of quality-controlled nodular cast iron (high-silicon, nickel, molybdenum nodular cast iron). This material has been used at temperatures of 1700 F.

Some other die materials that have shown promise for hot sizing are given in Table 3-27.1-1 with their probable limitations.

The use of ceramic materials for dies is a rather new development. One of these materials is a castable ceramic, and the holes for heater wires are cast into the die.[4] The ceramic faces of the die are covered with stainless steel sheets about 0.050 inch thick. Face temperatures higher than 1500 F are possible with these tools.

The clam-shell type of hot-sizing press may consist of a number of units incorporated into a single base and frame. They may be purchased as single units but installed side by side so that parts up to 40 feet long can be formed.[5] This design allows the use of multiple sections with a single long die, or individual use of each section with multiple small dies. This type of press is shown in Figure 3-27.1-1 with the part and dies used. Each unit has a 40 x 5?-inch platen that is equipped with its own clam-shell top closure and for hydraulic clamps. This unit can be used to hot size parts in any length up to 24 feet. Horizontal pressure is applied through the five hydraulic cylinders located in the rear of the press. Thus pressures of 1?0 tons are obtainable with each section. The horizontal cylinders will apply a maximum pressure of 75 tons each and are individually controlled.

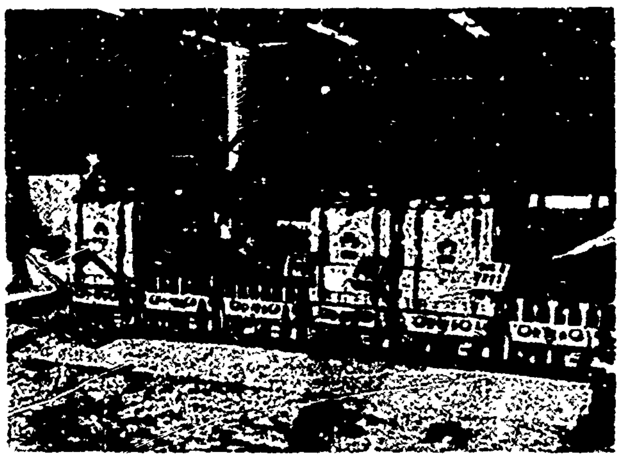


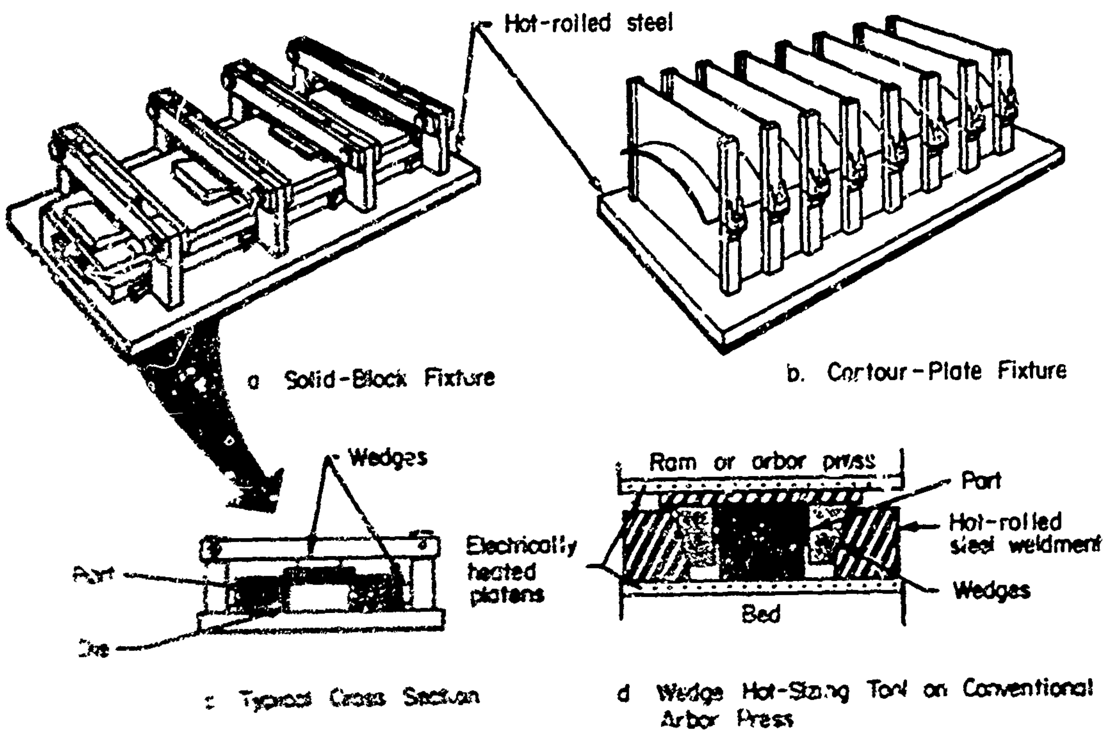
FIGURE 3-27.1-1. HOT-SIZING PRESS[6]

In the absence of hot-sizing presses, tooling can be made that will lock a part into position by driving wedges between retaining rings and the dies as shown in Figure 3-27.1-2. The locked-up die assembly is then placed into a furnace at the desired temperature for sizing. After the desired temperature and time cycle has been completed, the assembly is removed and air cooled. This technique has the advantage of using existing furnace capacity and permits the use of an inert

TABLE 3-27.1-1. SUMMARY OF TOOLING MATERIALS FOR HOT SIZING[1,2,3]

	Number of Parts	Temperature Limit, F	Remarks
Hot-rolled steel	<20	1000	Not recommended for production tooling because of scale problems
Meehanite[a]	<100	1200	Wire brush at intervals of 35 to 50 parts; light sand blast after 100 parts; good resistance to oxidation
Nodular cast iron[b]	>100	1700	
Stabilized H13	200	1000	
Type 310 stainless steel	200	1500	
Type RA330 stainless steel	>200	1450	
Inconel	>200	1450	
Hastelloy	>200	1450	
Ceramic[c]		>1500	Ceramic dies are covered with stainless steel sheets, 0.050 inch thick
Modified H13[d]	>100	1300	Prehardened to R_C 32 to 36.

(a) Meehanite is quality-controlled, high-silicon cast iron.
(b) High-silicon, nickel, molybdenum nodular iron.
(c) Produced by Glasrock Products, Torrance, California.
(d) A chromium, molybdenum, vanadium tool steel produced by Columbia Tool Steel Company, Chicago Heights, Illinois.



a. Solid-Block Fixture

b. Contour-Plate Fixture

c. Typical Cross Section

d. Wedge Hot-Sizing Tool on Conventional Arbor Press

FIGURE 3-27.1-2. HOT-SIZING FIXTURES[4]

atmosphere around the part and tooling, which reduces scaling and contamination. However, the attainable pressure in any one direction is limited by the retaining-ri strength at sizing temperature.

3-27.2 HOT-SIZING FORMING LIMITS

The hot-sizing process is used only for correcting springback in parts that have been formed by other processes. Consequently, no forming limits can be given. The removal of springback depends on two factors: time and temperature. The higher the temperature the shorter the time for processing. The effect of temperature on the material properties, however, limits the maximum useful temperature. The force applied to the part during hot sizing has little effect other than keeping the part tight against the tooling. Any additional pressure, over and above this requirement, has no effect on the part and may cause deformation of the tooling.

3-27.3 HOT-SIZING CONDITIONS

In operation the press platens are kept at a temperature of 1000 F or above to reduce the possibility of distortion during heating and cooling. Generally, the platens are heated electrically with integral cartridge-type heaters. The temperature is controlled by thermocouples embedded in the platens. The dies are preheated to the forming temperature before they are placed on the platens to reduce thermal shock. Dies and platens are insulated along the sides to prevent undue heat loss. The dies are maintained at the desired temperature by heat transfer from the platens and controlled by thermocouples in the platens.

The time at temperature is more important than the pressure in hot sizing parts. For Ti-8Al-1Mo-1V at 1450 F, little more than the weight of the dies is necessary to form the part to final dimensions. The pressure should always be kept to a minimum to prevent damage to the dies. Typical temperatures and times for sizing a number of alloys is given in Table 3-27.3-1.

The temperature of hot sizing is generally as high as is compatible with the tooling and equipment and the condition of the alloy being formed. The use of excessive temperature for a heat-treated alloy will result in structural degradation of the part.

3-27.4 SELECTED REFERENCES ON HOT-SIZING

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TABLE 3-27.3-1. SUGGESTED SIZING CONDITIONS FOR A NUMBER OF TITANIUM ALLOYS[4,7,8,9,10]

Alloy	Suggested Sizing Temperature, F	Time at Temperature, min	Remarks
Unalloyed	900-1000	3	Blank heated by contact with heated die
Ti-8Mn	900-1000	3	Blank heated by contact with heated die
Ti-5Al-2.5Sn	1200	15	0.032-in. -thick sheet
	1200	20	0.063-in. -thick sheet
Ti-8Al-1Mo-1V	1450	15	Ceramic dies used
Ti-3.25Mn-2.25Al	1000	3	3000-psi lateral pressure
	950	20	1500-psi lateral pressure
Ti-6Al-4V	1200	3-15	0.032-in. -thick sheet
	1200	3-20	0.063-in. -thick sheet
Ti-16V-2.5Al	600	15	0.040-in. -thick sheet
Ti-4Al-3Mo-1V	1075	20	0.037-in. -thick sheet, solution treated and aged
Ti-13V-11Cr-3Al	1100	(a)	0.065-in. -thick sheet, solution treated; aged after sizing

(a) Time at temperature not stated, but presumed to be 10 to 20 minutes.

SECTION 4

Joining Technology

4-0 General Comments on Joining

4-0.0 INTRODUCTION

Considerable use of joining processes is an obvious necessity in the fabrication of almost any product. This is particularly true of any structure as complex as the airframe of an aircraft. All airframes contain a multiplicaity of joints. Historically, most joints in the primary structures of aluminum airframes have been made with rivets or other types of mechanical fasteners. Although some attempts have been made to expand the use of other joining methods, the basic procedures have remained unchanged. The high-strength aluminum alloys used in past and current airframes are not easily welded. Welded joints in these alloys also have been suspect, with some justification, since reliability with some joining methods is poor and other methods result in degraded properties.

The importance of being able to employ specific joining procedures for the fabrication of a given aircraft is difficult to measure. The advantages of using a particular joining method can be offset by compromises in design allowables, range, payload, and many other factors. Some aircraft designs are obviously more sensitive to the exact joining procedures that are proposed than are others. In the proposed titanium airframes for advanced aircraft, it appears that the use of joining techniques other than mechanical fastening for many of the required joints offers the best approach to obtaining a minimum aircraft weight.

The joining processes that have been proposed for use on advanced titanium airframes are good selections for the intended use. Welding of the 8Al-1Mo-1V titanium alloy, which is likely to be employed extensively, is readily accomplished. More data are needed on weld-joint properties. Imagined or real difficulties with the proposed approaches are likely to be encountered in any program comparable in complexity to high-performance-aircraft-development programs. Potential problem areas appear to be well recognized, and a start has been made to determine whether any significant problems do exist.

4-0.1 JOINING PROCESSES

Many individual joining processes may be used in fabricating a titanium airframe. The individual processes have been grouped together for discussion under appropriate headings as follows: (1) welding, (2) brazing, (3) metallurgical bonding, (4) adhesive bonding, (5) mechanical fastening. The first four types of joining processes produced permanent joints. Thus, replacement or repair requires removal of an entire unit or local cutting and rework. Mechanical fasteners are used for joints that may be either permanent or semipermanent. Mechanical fasteners are always used in joints that have to be taken apart periodically and in major assembly breaks.

Of the five types of joining processes being considered, only welding is markedly sensitive to the choice of titanium alloy. The remaining processes can be applied to titanium alloys with about the same degree of success regardless of the specific alloy selected.

Available information on each joining process is covered in more detail in the sections that follow. In each section, the important factors pertinent to the joining of titanium by the process being discussed are covered. Background information about the process itself is also included for completeness.

4-0.2 WELDING

Welding processes can be used extensively to join major components of high-performance titanium airframes. The selection of welding for these uses comes about for several reasons:

(1) Welding is a low-cost joining method

(2) Welding is a particularly suitable joining method for certain titanium alloys

(3) Welding results in a minimum-weight aircraft structure

(4) Weld joints are generally strong and leaktight.

The suitability of any material for use in a welded structure (weldability) is very dependent on service conditions. Weldability by definition involves two distinct criteria:

(1) The ability to physically produce a welded joint

(2) Satisfactory performance of the welded part in the intended service.

Very few titanium alloys fail to meet the first weldability criterion. The ability to meet the second criterion can only be demonstrated by performance in service. However, a good estimate of the second weldability criterion can be obtained from careful planning and test programs designed to simulate characteristics critical to performance.

In an airframe, it is believed that the critical characteristics from a weldability standpoint are:

(1) Mechanical-property stability over the design temperature range for the airframe lifetime

(2) Fatigue and fracture propagation characteristics of welded joints.

4-0.2.1 Basic Processes

The welding processes that may be used on titanium aircraft structures include:

(1) Fusion Processes

(a) Inert-gas-shielded tungsten arc - also called TIG or GTA

(b) Inert-gas-shielded metal arc - also called MIG or GMA

(c) Inert-gas-shielded arc spot - this method may employ either the basic TIG or MIG process

(d) Electron beam (EB).

(2) Resistance Processes

(a) Spot

(b) Roll spot

(c) Seam.

Table 4-0.2.1-1 shows some of the basic characteristics of these welding processes.

In addition, upset-welding processes may be used to fabricate special sections or mill products. These are:

(a) Flash - to produce components from bar stock, forgings, extrusions, or tubing

(b) Induction pressure - to produce components from bar stock, forgings, or extrusions

(c) Gas pressure - to produce components from bar stock, forgings, or extrusions

(d) High frequency - to produce structural shapes or stiffened panels.

The process groupings given above have been set up because of the many similarities between processes in each group. The reasons will be more apparent from the following sections.

4-0.2.2 Uses

The varied characteristics of welding processes lead to a very broad range of possible uses. Most titanium joints in an airframe could be completed by one or more welding processes. However, welding is expected to find major usage in subassembly fabrication and a few large structural

TABLE 4-0.2.1-1. CHARACTERISTICS OF WELDING METHODS FOR TITANIUM

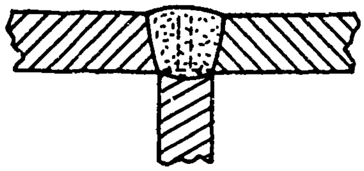
Characteristic	TIG, GTA	MIG, GMA	Arc Spot	Electron Beam	Resistance Spot and Seam
Usefulness	Excellent	Fair	Good	Fair	Good
Production rate	Moderate	Fast	Moderate	Slow[(a)]	Fast
Applicable joint design	Butt, tee, lap, fillet	Butt, tee, lap, fillet	Lap only	Butt, tee, lap, fillet	Lap only access both sides
Applicable thickness	Any; best for thinner gages	Thicker gages only ≥ 0.125 inch	TIG-1/8t+1/8t MIG-above 0.2t	Any	Min ~ .01t+.01t Max ~ 1 in. total
Joint loading					
Tension	X	X	Limited	X	Limited
Shear	X	X	X	X	X
Compression	X	X	X	X	X
Bending: Tranverse	X	X	Limited	X	Limited
Bending: Longitudinal	X	X	X	X	X
Torsion	X	X	Limited	X	Limited
Resistance to thermal stress	Good	Good	?	Good	?
Thermal stability (Met.)		(Dependent on alloy composition)			
Corrosion	Good	Good	?	Good	?
Major limitations	None	Process control	Fatigue	Vacuum required	Fatigue
Normal usage	Manual or machine	Machine	Manual or machine	Machine	Machine
Ease of inspection	Good	Good	Fair	Good	Fair

(a) Electron-beam welding is the fastest of the methods shown, however, loading and unloading of parts in the vacuum chamber limits production.

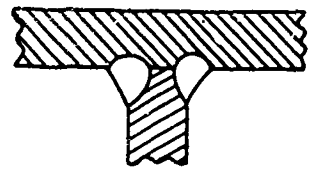
components (e.g., landing gear). Cost, maintenance, reliability, accessibility, and over-all component size are important factors in assessing the proper use of welding and alternate joining methods.

Some typical joint types that can be made by the various welding processes are shown in Figure 4-0.2.2-1.

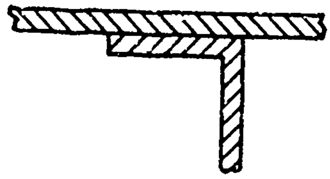
a. Butt (TIG, MIG, or EB)



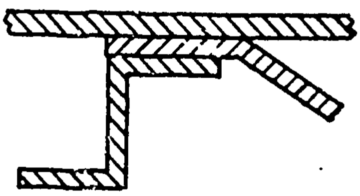
b. Fabricated Tee (TIG, MIG, or EB)



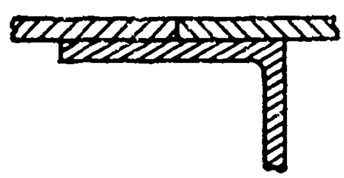
c. Fillet (TIG, MIG)



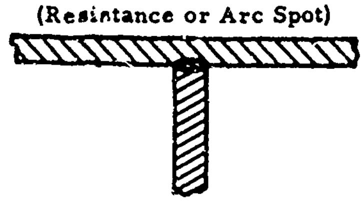
d. Sheet-Stringer Lap (Resistance or Arc Spot)



e. Multilayer Lap (Resistance or Arc Spot)



f. Sheet Splice with Doubler (Resistance or Arc Spot)



g. Cap or Tee (EB or HFRW)

FIGURE 4-0.2.2-1. TYPICAL TITANIUM WELD-JOINT DESIGNS

4-0.2.3 Relation to Other Processing

The relationship of welding to other fabrication operations is important in that fabricating operations immediately before and after welding are closely related to successful part fabrication by welding. Good joint fitups are needed, and all titanium parts must be properly cleaned before welding. Also, stress relieving of complex (and perhaps all) weldments immediately after welding should be carefully considered.

4-0.2.4 Material Characteristics

Welding of titanium alloys is readily accomplished as long as the basic nature of the alloys is understood. Four principal characteristics important in welding titanium are:

(1) The high chemical activity of titanium at elevated temperature

(2) The significant changes in mechanical properties of welded titanium caused by very small amounts of elements that form interstitial solid solutions in titanium

(3) The effects on the mechanical properties of titanium and stability in the base material. Both pre- and postweld treatments are involved in accomplishing this.

Each of these characteristics is discussed in Section 1 in detail. In the following sections, these characteristics are discussed only as they relate to welding. Some repetition of Section 1 was deemed warranted for emphasis.

4-0.2.4.1 Chemical Activity

Titanium and titanium alloys react with air and most elements and compounds, including most refractories, when heated to welding temperatures. As a result, gas fusion and arc-welding processes where active gases and fluxes are in contact with the hot metal are not usually used because the welds are embrittled by the reactions that occur. However, inert-gas-shielded or electron-beam fusion welding and spot, seam, flash, and induction-pressure welding may be used. With the inert-gas-shielded arc-welding processes, argon or helium shields the

welds from air and prevents weld contamination. Electron-beam welding takes place in a vacuum. In spot and seam welding, the molten titanium in the weld is surrounded by the titanium base metal, so the welds are protected from contamination. In flash and pressure welding, air may be in contact with the weld, but most of the contaminated metal is pushed out of the weld area, and any remaining impurities diffuse into the metal away from the weld interface.

4-0.2.4.2 Interstitial Elements

Of the few elements that can form interstitial solid solutions in titanium, only carbon, oxygen, nitrogen, and hydrogen are of specific interest in the welding of titanium. Carbon, nitrogen, and oxygen all behave in about the same way in titanium. Increases in the concentration of these elements, even at very low total levels, cause significant decreases in the ductility and toughness of titanium welds. The effects of these elements on weld ductility and toughness are to some extent progressive and additive. Because of this, it is difficult to establish a definite amount of these elements that distinctly separates good and bad properties.

Carbon, oxygen, and nitrogen may be found in titanium weldments because of any of the following:

(1) They are deliberate alloying additions to some forms of titanium

(2) They may be present as residual impurities

(3) They may be picked up as contaminants from various processing steps.

Pickup of oxygen and nitrogen during welding operations must constantly be guarded against.

The basic behavior of hydrogen in titanium is somewhat different from that of the other interstitial elements; nevertheless its presence in titanium welds can be extremely harmful. Hydrogen is never deliberately added to titanium and should be kept at as low a concentration as possible in all processing operations.

The interstitial level that can be tolerated in welded joints depends on the use to which the welds will be put and the alloy that is being welded. Weld toughness is decreased by lower interstitial levels than those that will affect ductility. Therefore, greater care should be taken to insure against weld contamination in fabricating assemblies that are subjected to impact loading. Also, welds in some alloys are more ductile and therefore have a higher toughness than welds in other alloys. The interstitial level that can be tolerated in welds is related to their ductility and toughness. Higher levels can be tolerated in welds that have high ductility than in welds with low or marginal ductility. Unalloyed or lower alloy filler wire is often used to improve weld ductility.

The interstitial level that can be tolerated in welds is lower than the corresponding tolerance level in base material. Interstitials that are present in the base metals prior to welding or are introduced during welding may cause weld embrittlement. Titanium produced some years ago was much more likely to contain excessive interstitial content than is material currently being produced. Special titanium grades that are designated ELI (extra low interstitial) may be used extensively in welding particularly for welding filler wire.

4-0.2.4.3 Substitutional Elements

As in most metals, substitutional alloying elements affect the properties of welded joints in titanium. This is true both when the substitutional elements are present as a result of their having been added as alloying elements to the base metal or when they are present as a result of welding titanium to dissimilar metals.

The most generally recognized effects of substitutional alloy additions in titanium relate to the type of alloy formed by the specific addition or additions. As shown in Section 1, titanium alloys are classified metallurgically as either commercially pure titanium, alpha alloys, alpha-beta alloys, or beta alloys. These metallurgical properties in turn influence the way that the alloys behave in welding operations. The initial base material condition (cold worked or heat treated in some manner) is equally as important as alloy content, as will be shown in the next section.

4-0.2.4.3.1 Commercially Pure and Alpha Alloys

The mechanical properties that of welds in either commercially pure titanium or alpha alloys are not affected by welding operations on annealed sheet material. Alloys of this type that have been strengthened by cold working will exhibit a loss of strength in the welded zone. Very little use is made however, of cold working to increase the strength of either commercially pure or alpha-type alloys. Welded joints in alpha-titanium material are ductile and exhibit strengths that are equal to those of the base metal. Alpha alloys with a maximum of usable strength are obtained by using a level of substitutional alloy addition that is close to the maximum solubility. The 8Al-1Mo-1V titanium alloy is of this type, and is the highest strength alpha alloy currently available that exhibits good welding characteristics.

4-0.2.4.3.2 Alpha-Beta Alloys

Depending on the exact alloy content, the mechanical properties of alpha-beta alloys may be altered greatly by heat treatment. Also, the ductility of many of these alloys is changed significantly by variations in heat treatment. Thus, welding these alloys may significantly change the mechanical properties. With the alpha-beta alloys, very few generalized statements about weldability can be made. The selection of this type of alloy for use in an application requiring welding should be based on the known effects of the alloy content and the intended application. Alloys that contain about 3 percent of either chromium, iron, manganese or molybdenum and more than 5 percent of vanadium either singly or in combination with each other are not used in fusion welding applications because of resulting low weld ductility. Even with alloys containing percentages of these elements in excess of the amounts given above, it is sometimes possible to improve weld ductility by a postweld heat treatment. However, the use of heat treatment is not always effective in improving ductility. The thermal stability of welded alpha-beta alloys is another area of concern if the intended application involves prolonged service at elevated temperatures. Again, no generalized statements are possible in this area, and data should be examined for each specific alloy.

Alpha-beta alloys are sometimes welded with either commercially pure or alpha-alloy filler metals This is done to lower the alloy content of the weld fustion zone. The use of filler metals of this type lowers the beta content of the fusion zone and generally results in improved weld ductility and toughness. However, the use of special filler metals does not alter the composition of the heat-affected zone of a weld. In alpha-beta alloys that are characterized by a relatively brittle heat-affected zone, the use of special filler-metal alloys is ineffective in obtaining an overall improvement in weldment properties.

4-0.2.4.3.3 Beta Alloy

The all-beta alloy, Ti-13Cr-11V-3Al, depends very strongly on either cold work or heat treatment to obtain desirable strength properties. In these conditions, welded joints are readily made, but the resulting weld strength is considerably lower than that of the base plate. Postwelding operations designed to raise the weld strength level are either not practical or result in severe embrittlement of the beta alloys. The reasons for this are not well-known, but are apparently related to different aging responses of structures that differ in grain size, grain structure, or orientation. All-beta alloys are also susceptible to thermal instability. Their use in a fully annealed condition is generally not warranted because of the low strengths available

4-0.2.4.3.4 Dissimilar-Metal Joints

Titanium is difficult to weld to steels, aluminum, nickel, and copper alloys because brittle structures generally result when it is highly alloyed with these metals. Highly alloyed structures are formed in the fusion zones of welds that are made with processes that result in melting of both base metals. These highly alloyed zones contain intermetallic compounds and are extremely brittle. Columbium, molybdenum, tantalum, and zirconium are more compatible for welding to titanium than are steel, nickel, and copper. When titanium is highly alloyed with columbium, molybdenum, tantalum, or zirconium, brittle intermetallic compounds are not formed. However, the resulting solid solutions are of an extremely high alloy content, and the joints between titanium and these metals may have little ductility.

4-0.2.4.4 Strengthening Mechanisms

Titanium alloys are strengthened by several mechanisms. These include cold working (strain hardening) and heat treatments. The discussion required to explain strengthening mechanisms of titanium is presented to a limited extent in Section 1 on Titanium Metallurgy. The various strengthening mechanisms used in titanium are primarily important from a welding standpoint because of the way they affect the weldability of alloys as based on mechanical-property tests. Some alloys are considered to be weldable if the welds are not given any postweld heat treatment. However, quite often welds in such alloys are much lower in strengths than the heat-treated base metals. Attempting to increase the strength by a postweld heat treatment may be successful, but quite often some other property (such as ductility) is degraded.

The importance of strengthening mechanisms as a consideration in the weldability of titanium alloys can be illustrated in another way by considering the following statements.

(1) The properties of titanium-base alloys are determined by alloy content and a controlled mechanical and thermal processing history.

(2) Welding imposes variable thermal cycles on material in the joint area that are unlike any other exposure conditions normally used on titanium alloys.

(3) The effect of welding thermal cycles on the properties of titanium alloys may be insignificant or very significant

(4) The apparent weldability of any given titanium alloy can be altered considerably by either the initial base-material condition or postweld thermal or mechanical treatments

4-0.2.5 Preweld Cleaning

Proper surface preparation before welding is important to (1) remove scale, dirt, and foreign material that might contaminate the welded joint, (2) insure uniform surface conditions and thereby improve weld consistency in spot- and seam-welding operations, and (3) help control weld porosity in arc-welding operations.

4-0.2.5.1 Grease and Oil

Degreasing operations are used to prepare scale-free material for welding and to prepare materials with an oxide scale for descaling operations. Degreasing may be accomplished in any of the following ways.*

(1) An alkaline wash or dip. This is a dilute solution of sodium hydroxide; about 24 ounces of NaOH per gallon of water is typical

(2) A solvent wash. Typical solvents that are used are MEK, methyl alcohol, toluene, and acetone

(3) Hand wiping with solvent immediately before welding. The use of excess solvent during wiping should be avoided.**

Chlorinated solvents, such as tricholorethylene, should not be used to degrease titanium. Stress-corrosion cracking in weld areas during subsequent processing has been attributed to the use of chlorinated solvents.

4-0.2.5.2 Light Scale

Acid pickling treatments are used to clean titanium that has a light oxide scale. The scale formed on titanium at temperatures up to about 1100 F is generally thin and may be removed by acid pickling. The most commonly used pickling baths are the HF-HNO_3 solutions. These baths contain from 2 to 5 percent HF and 30 to 40 percent HNO_3. And are used in the range from room temperature to 140 F. A fairly common treatment is to use a bath containing 35 percent HNO_3 and 5 percent HF (by weight), balance water. Parts to be pickled are immersed for 30 seconds.*** After pickling, the materials are rinsed in water and dried. Pickling treatments also are used to prepare scale-free material for spot- and seam-welding operations. Pickling should be avoided on assemblies that contain crevices or lapped joints that may entrap the acid solution.

4-0.2.5.3 Heavy Scale

Scale formed at temperatures above 1100 F is thicker than that formed below 1100 F and is difficult to remove chemically. Molten-salt baths, which are basically sodium hydroxide to which oxidizing agents have been added or to which hydrogen has been added to form sodium hydride are commonly used to remove this scale in preparation for welding. Caution is needed in using these molten salt baths. Bath compositions and temperatures must be carefully controlled to prevent the introduction of excessive amounts of hydrogen into the metal. Also, mechanical methods such as vapor blasting and grit blasting are used. Both the molten-salt-bath treatments and mechanical scale-removal operations are followed by a pickling operation to insure complete scale removal and to remove subsurface contaminated metal if necessary.

4-0.2.5.4 Handling and Storage

All part handling after cleaning and before welding must be controlled. So-called "white-glove" operations are in order to prevent negating the desired control obtained through careful cleaning. Cleaned material should be welded as soon as possible after cleaning, or wrapped for storage until needed. Some recleaning of material that has been in storage may be required.

4-0.2.6 Postweld Cleaning

Welded parts that are to be hot formed or stress relieved must be clean as noted in Section 3. In view of the problems in cleaning complex parts, it may be much simpler to keep such parts from getting dirty during welding. This will require careful handling and storage throughout all operations associated with the actual welding.

4-0.3 BRAZING

Brazing is not expected to be used in a major way as a joining method on titanium airframes in

*Good rinsing and drying procedures are important in these operations. Residue from the degreasing treatment must not be allowed to remain in the joint area.

**Do not use rubber gloves for this type of operation. Reactions between solvents and some of the compounds in gloves can leave deposits on the joint that cause porosity.

***About 0.0003 inch of material is removed from all surfaces of commercially pure titanium by this pickling.

the near future. Brazing has some advantages over other joining processes in the fabrication of titanium sandwich structure, and in the completion of dissimilar-metal joints. Despite the great potential for these two areas, most of the programs that have been conducted to complete required developments have not produced universally acceptable procedures for completing such joints. The major development work that has been conducted on titanium brazing is related to two areas: (1) the development of materials and procedures to allow the use of brazed titanium sandwich structure, or (2) the development of brazing procedures for fabricating dissimilar-metal joints.

Most of the problems encountered in attempting to braze titanium are related in one way or another to the characteristics of titanium metal. Titanium's high affinity for other elements leads to a requirement that brazing be conducted under conditions that prevent contamination of the material being joined. Also, because of its high reactivity, it is difficult to find suitable braze filler metals that do not react excessively with the titanium base material producing subsequent embrittlement or serious erosion of the base metal. The final problem area has been one of finding brazing filler metals suitable for use in brazing thermal cycles that are compatible with the limited thermal heat-treatment cycles that can be used on titanium alloys.

4-0.4 METALLURGICAL BONDING

In metallurgical bonding, joints are formed with all components of the joining system being maintained as solids. Joints can be made under these conditions if two metallic surfaces, which have been prepared properly, are brought together by an applied pressure at a suitable temperature for a suitable length of time. Deformation and diffusion are important aspects of metallurgical bonding. It is convenient to further subdivide this type of bonding on the basis that either deformation or diffusion is the predominant mechanism contributing to joint formation. Actually, both mechanisms always operate to some extent during the formation of a joint, but there are significant differences in the extent to which these two mechanisms control a given bonding process. Deformation is limited to very small surface areas during bonding, which is controlled primarily by diffusion mechanisms. When considerable deformation is used during the bonding operation, diffusion can be quite limited. Both deformation and diffusion bonding have been employed successfully on titanium.

Metallurgical bonding is used to describe many joining processes that may be referred to by a number of different names. As used in this handbook, the term metallurgical bonding is intended to cover all solid-state joining processes in which either diffusion or deformation plays a major roll of the formation of the joint. Resistance-diffusion bonding, which could be covered in this section, is covered in Paragraph 4-2.1, Resistance Spot Welding, because of its many similarities with that process. Some of the other names used for the processes covered here under Metallurgical Bonding are:

(1) Solid-state welding or bonding
(2) Diffusion bonding
(3) Pressure bonding
(4) Gas-pressure bonding
(5) Roll bonding
(6) Deformation bonding
(7) Vacuum bonding or welding

4-0.4.1 Diffusion Bonding

In diffusion bonding, deformation is limited to that amount required to bring the surfaces to be joined into intimate contact. Once the surfaces are in contact, a joint is formed by diffusion of some element or elements across the previously existing interface. Diffusion bonding is primarily a time- and temperature-controlled process. The time required for bonding can be shortened considerably by using bonding pressure or elevated temperatures, since diffusion is much more rapid at high temperatures. Both the bonding time and temperature often can be reduced by using an intermediate material of different composition to promote diffusion bonding. This procedure reflects the increase in diffusion rate that is obtained by the introduction of a dissimilar metal. The steps involved in diffusion bonding are:

(1) Preparation of the surfaces to be bonded by cleaning or other special treatments

(2) Assembly of the components to be bonded

(3) Application of the required bonding pressure and temperature in the selected bonding environment

(4) Holding under the conditions prescribed in Step 3 for the required bonding time

(5) Removal from the bonding equipment for inspection and/or test.

The preparation step involved in diffusion bonding usually includes a chemical etching and other cleaning steps similar to those employed during welding or brazing. In addition, the surfaces to be bonded may be coated with some other material by plating or vapor deposition to provide surfaces that will bond more readily. Coatings also are sometimes applied to prevent bonding in certain areas. The methods used to apply pressure include simple presses containing a fixed and movable die, evacuation of sealed assemblies so that the pressure differential applies to a given load, and placing the assembly in autoclaves so that high gas pressures

can be applied. A variety of heating methods also can be used in diffusion bonding, but generally the temperature is raised by heating with some type of radiation heater. As suggested above, the environment during bonding is another important factor during this type of joining. With titanium, a vacuum environment is most practical, although it is possible to bond in an inert gas.

Diffusion-bonded joints have been made in titanium and several of its alloys* at selected conditions encompassing the following ranges.

Temperature	1500 to 1900 F
Time	30 minutes to 6 hours
Pressure	5 to 10 ksi

In all cases, the environment during bonding was a vacuum. Some success has been reported with the diffusion bonding of titanium employing an intermediate material to either decrease the bonding temperature or the required time. The usefulness of this method with titanium is limited by the difficulty in finding a suitable intermediate material that will not react excessively with the titanium to form either brittle intermetallic compounds or other undesirable phases.

4-0.4.2 Deformation Bonding

Deformation bonding differs from diffusion bonding primarily in that a measurable reduction in the thickness of the parts being joined occurs with deformation bonding. The large amount of deformation involved makes it possible to produce a bond in much shorter times and frequently at lower temperatures than are possible during diffusion bonding. The major application of deformation bonding of titanium to date has been in the fabrication of roll-welded sandwich structures. With this process, unidirectional structural panels having either a corrugated or ribbed structure have been reproduced. In addition, the process shows promise for the fabrication of structural shapes such as tees or I beams.

The steps involved in deformation bonding are very similar to those involved in diffusion bonding. The major difference is that bonding is usually accomplished in a very short time by passing the object to be bonded through some device such as a rolling mill, which applies the desired pressure and produces the proper deformation for bonding. A major advantage of the roll-welding approach to producing either sandwich or structural shapes is that the parts can be formed to any desired contour immediately after the bonding.

*Ti-5Al-2.5 Sn, Ti-8Al-1 Mo-1V, Ti-6Al-4V, Ti-3Al-2.5 Sn, and Ti-5Al-1.25Fe-2.75 Cr titanium alloys.

4-0.5 ADHESIVE BONDING

Adhesive bonding may be used in the fabrication of titanium airframes to either replace or complement other joining processes. Opinions as to the usefulness of adhesive bonding appear to vary widely within the aircraft industry. The known advantages of this method of joining are offset to some extent by known disadvantages. Factors that are considered to be critical in determining the usefulness of adhesive bonding in an airframe are: (1) demonstration that adhesive-bonded joints will withstand long periods of service at the elevated temperatures involved in the application and (2) demonstration that reliable process-control techniques have been developed that will insure that reproducible joint properties can be obtained.

Adhesive bonding shares many factors in common with other joining techniques. Reproduction of good adhesive-bonded joints requires consideration of the materials, the processing, equipment, and subsequent exposure conditions. The principal material involved in adhesive bonding is the adhesive itself. A wide variety of chemical compounds have been used for adhesives. These materials can be classified as thermoplastic, thermosetting, elastomeric, ceramic, and blends of the first three types. Thermosetting and ceramic adhesives appear to have the most potential for use in the anticipated supersonic temperature ranges.

Once a suitable adhesive is identified for use in metal adhesive bonding, further development is still required to ensure that any given material can be successfully processed to form suitable joints. A major factor in this processing is the treatment of the metal surfaces that are to be joined. Significant difference in joint properties occur because of variations in the surface treatment of the metal. The successful use of titanium adhesive-bonded joints will require that reliable surface-treatment methods be developed.

Equipment for adhesive bonding of titanium is not expected to be a problem. The same general types of equipment that are used successfully in the adhesive bonding of other materials should prove applicable.

The ability of adhesive-bonded joints to withstand long-time elevated-temperature exposure must be demonstrated in the same way as for other types of joining. Most of the data that have been obtained to date are for relatively short exposure times compared with the intended service life of a supersonic transport. Recently developed polyimide-based adhesives have shown relatively high strengths after prolonged exposure at elevated temperatures. There still appears to be a need for much more extensive long-time elevated-temperature testing of adhesive-bonded joints prior to their acceptance for use in a supersonic transport.

4-0.6 MECHANICAL FASTENING

The traditional methods of assembling airframe structures are bolting, riveting, latching, or using specialized mechanical fasteners. These mechanical fastening methods will continue to be used in supersonic titanium airframes, particularly for nonpermanent joints. Preparation of the titanium structural components for mechanical fastening will differ from the procedures for such materials as aluminum and steel to the extent that the machinability of titanium alloys differs from other metals. As in all aircraft-quality fastening, bolt and rivet holes must be smoothly machined within tolerances, burr-free, and clean. Cleanliness with respect to freedom from carbonaceous, chloride-bearing, or other cutting fluids is particularly important in titanium airframes intended for high-temperature service, since titanium reacts chemically with carbon, hydrogen, and oxygen.

Titanium bolts are commercially available. Most are fabricated from the Ti-6Al-4V alloy by conventional forging and cold heading operations. Titanium rivets are also available, but there is a significant usage of Monel, A286, and aluminum rivets for fastening titanium.* Fastening with dissimilar metals raises the possibility of galvanic corrosion in the presentce of aqueous electrolytes unless the fasteners could be electrically isolated from the titanium. Considering the deformations and stresses inherent in the bolting and riveting operations, reliable isolation of the large number of fasteners to eliminate galvanic corrosion appears to be difficult.

Galling and seizing also are problems encountered in using titanium fasteners. In addition to the obvious problems caused by these actions, they may also degrade fatigue life of the fastener. Selection and use of suitable lubricants may assist in overcoming these difficulties.

In riveting with titanium rivets, heating of the rivets prior to driving has been found to be desirable in at least some cases to avoid cracking. In this respect, titanium riveting procedure differs from aircraft aluminum practice and becomes more akin to structural steel riveting.

4-0.7 JOINT PROPERTIES

Joint properties are extremely important in assessing the ultimate usefulness of any joining process. Design engineers must know the characteristic load-carrying ability of any given type of joint, and, in addition, must be satisfied that the load-carrying ability will not be changed significantly during service of the joint. With this in mind, it is obvious that the determination of properties of a joint that make it suitable for a certain type of service must be made with the particular service in mind. Of particular concern in aircraft applications are the temperature-exposure spectrum and the anticipated load spectrum. Methods of evaluating joints vary considerably, depending upon the purpose of the evaluation, the joining process, material and thickness involved, and on the needs of the particular individual conducting the evaluation. These varying requirements have led to the development of many different tests and test specimens, which range in size from extremely small specimens that represent only a portion of a structure to complete structural tests. Any small-test specimens can reflect only the expected behavior in a structure in terms of a statistical average and with an accuracy set by the degree to which the test conditions relate to the service conditions. This is true of any type of test specimen. With joint specimens, there are other complicating factors that result in the need to use different methods in evaluating joints from those used in evaluating base material.

Designers and production engineers are constantly faced with joint-property evaluations. Designers are primarily interested in the allowable stresses for a given joint. Production engineers are more concerned with producibility and quality control. Each group has developed joint test specimens to meet their particular needs. Standardization of test-specimen geometry and testing procedure unfortunately is not always the case. In the area of joining, seemingly minor variations in such procedures or in the procedures used to produce the joints may result in significantly different observed properties. Thus, any tabulation of property data that is presented without the allied backup data pertaining to fabrication and test procedures should be viewed with caution.

Further comments on determining joint properties are summarized in DMIC Report 165 (December 28, 1961), "Methods of Evaluating Welded Joints". This report is based in part on surveys conducted by DMIC and the Aerospace Research and Testing Committee (ARTC) of the Aerospace Industries Association. The ARTC effort was conducted as Project 28-58, "Standardization of Welded Joint Specimens".

Eventually, most joints are evaluated in full-scale tests. This is required to validate final joint designs because of the complex problems that prevent even computer analyses. The most important fact that should be remembered about joint properties is that no single property is indicative of performance. Joints must be evaluated by an analysis of the properties obtained in a number of different tests.

Joint properties are controlled in manufacturing operations by quality-assurance programs largely based on process specifications.

*Caution should be exercised in selecting nontitanium fasteners for elevated-temperature service to ensure that low-melting fastener coatings are not used.

4-1 Fusion Welding Processes

4-1.0 INTRODUCTION

Fusion welding is often used to categorize welding processes in which joining is accomplished by heating to the melting point using an external heat source. In this handbook, the term is used to describe processes with similar basic characteristics. The prime processes of interest here are TIG, MIG, EB, and Arc spot. Characteristically, in these processes a localized joint area is heated to the melting point. The molten metal extends over a certain zone and then freezes to form the final weld. Metal that is melted is called weld metal. Metal around the joint that is changed in some way by the heat involved is called heat affected.

All the fusion-welding processes share certain common characteristics. These are discussed in the following section. Subsequent sections discuss each process separately.

4-1.0.1 Cleaning

Careful preweld cleaning is essential to successful fusion welding of titanium alloys. The procedures for cleaning discussed in Paragraph 4-0.3.5 will provide material meeting many welding requirements. Poor cleaning can result in weld contamination with interstitial elements and weld defects, particularly porosity. To control porosity in fusion welding, the edges to be joined and adjacent surfaces are given special cleaning treatment by some fabricators. These treatments include draw filing, wire brushing, or abrading the joint edges and adjacent surfaces prior to fitup and an acetone or alcohol wipe just prior to welding. Special treatments are discussed in detail in Paragraph 4-1.0.14.1.

4-1.0.2 Joint Design

Suitable joint designs must be selected for fusion welding. Joints with square abutting edges are suitable for the thinner gages of titanium.* Thicker gages may require a joint preparation. Typically, such preparation involves machining bevels or contours on the abutting edges. Part tolerances also are an important consideration in establishing good joint designs. Close tolerances are always preferred, but they cannot always be planned for in production parts. With titanium, it is also essential that the joint design selected be one that can be properly shielded from contamination.

*Even thin gages of titanium may have to be machined to avoid weld porosity. Sheared edges have been found to increase the tendency for porosity formation, probably because any burrs or smeared-over metal can entrap dirt.

4-1.0.3 Base Metal

Titanium-base metals of proven quality must be provided for fusion welding. Adherence to standards for composition, grade, and heat-treatment condition is a must. Either alloy or interstitial element segregation can be a source of trouble in fusion-welding operations. Contamination of the base-metal surface layer during operations preceding welding should be avoided or steps provided in the processing to remove the contaminated layer. Such contamination is not just a surface phenomena, but may extend for a measurable depth.

4-1.0.4 Wire

Some fusion-welding processes involve the addition of metal from sources other than the base metal. Wire is generally used, since it is easy to add at a controlled rate. Wire added during TIG welding is called "filler wire" or "cold wire". Wire used in MIG welding also is called filler wire, or it may be called "electrode wire".

Titanium wire for welding must meet high-quality standards. The same is true for most welding wire. This requirement results from the high surface-area-to-volume ratios characteristic of the common wire sizes used in welding (see Figure 4-1.0.4-1). Obviously, any wire surface-layer contamination represents a sizable addition to a weld. Also, it is much more difficult to process titanium to wire without contamination than is the case with other products. For example, wire cannot be processed by any method comparable to the pack-rolling procedures used for thin sheet.

Wire products sometimes contain defects. The terminology used to describe various wire defects is illustrated in Figure 4-1.0.4-2. None of these defects can be tolerated in titanium wire intended for welding structural components of high-performance airframes.

The availability of good-quality titanium welding wire in the past and today has been debated extensively.[1] Some welding engineers feel that high-quality titanium wire just does not exist. Others do not think there is a "welding-wire problem". The real answer probably lies somewhere between these two extremes.

The "titanium welding-wire problem", if there is one, must be resolved before some fusion-welding processes can be used on airframes. Titanium welding-wire development has suffered from the lack of a sizable market. Unalloyed cp titanium wire has been the major marketable item. Experience with the various titanium alloys has been limited. The required wire-quality level and

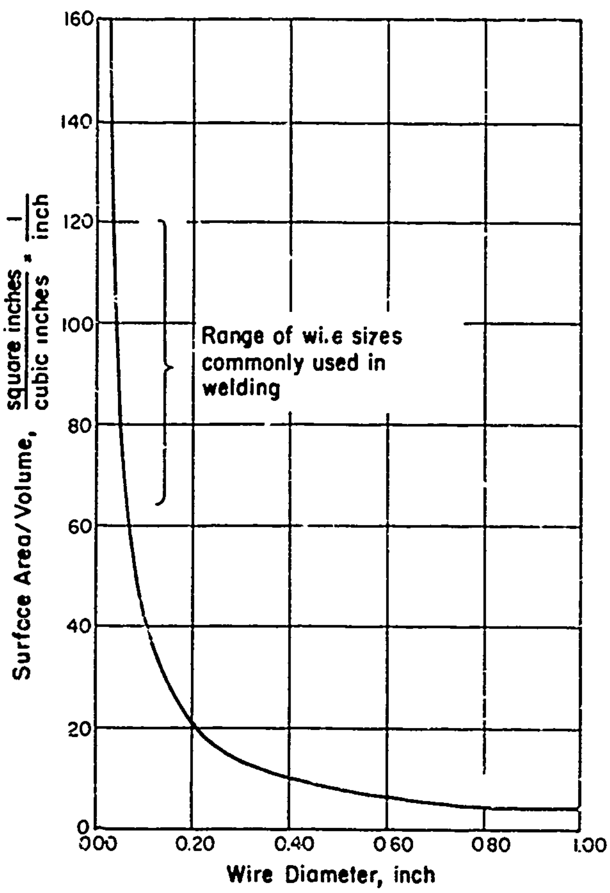


FIGURE 4-1.0.4-1. SURFACE-AREA-TO-VOLUME RATIO FOR SEVERAL WIRE SIZES

and reliability in alloys like Ti-8AlMo-1V can probably be developed once a market is evident.

Titanium welding wire is supplied by all of the major titanium companies and by several companies specializing in processing high-quality metals and alloys. The specialty suppliers are listed in Section 2.

4-1.0.5 Inert Gas

Inert gases, argon and helium, are used for shielding with all fusion-welding processes except electron beam. High gas purities are needed in welding titanium. Special grades of inert gas containing additivies, such as oxygen, that are used in some welding, should not be used in welding titanium. Basic inert-gas supplies are of the required quality. The major concern with inert gas is insuring that the basic gas quality is not degraded during flow through the welding equipment. The number of disconnectable fittings used in the gas system should be minimized. All such fittings must be kept in good condition and must be tight.

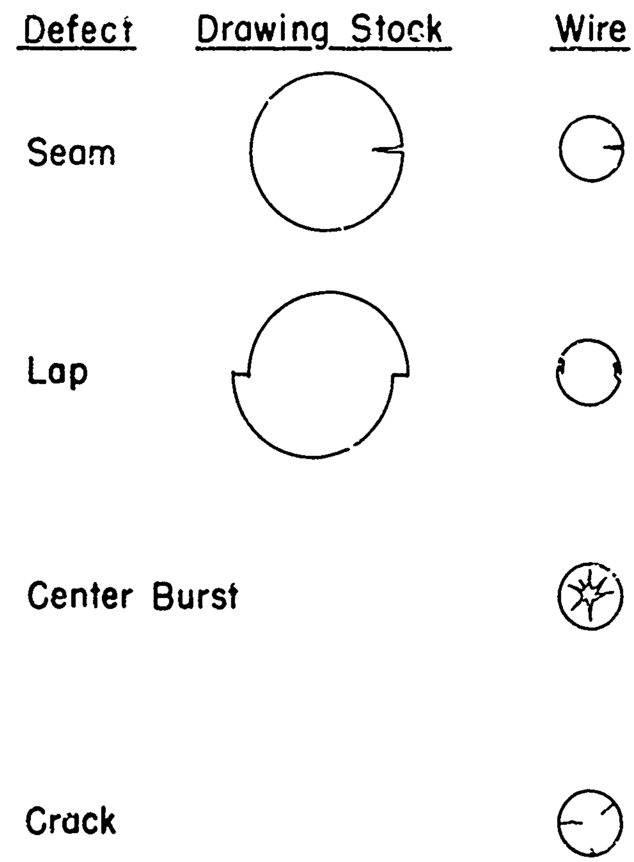


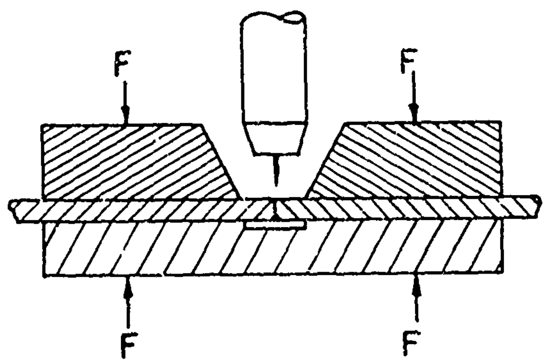
FIGURE 4-1.0.4-2. WELDING-WIRE DEFECTS

Damaged or loose fittings can allow air to be entrained in the inert gas, resulting on contamination of the weld.

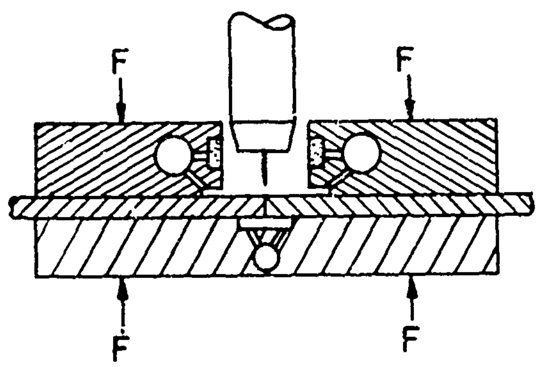
4-1.0.6 Tooling

The tooling used in welding titanium may differ markedly from tooling normally used in welding other materials. Tooling per se may range from simple clamps to hold parts in position to more elaborate holding devices designed for specific parts. Simple tooling is adequate for welding titanium when other means are used to insure adequate shielding; for example, in electron-beam or arc welding in an enclosed chamber. However, for fusion-welding operations conducted outside of chambers, tooling can provide a much more effective safeguard against weld contamination than other shielding devices. Tooling often is used to cool the weld area rapidly sothat exposure in the temperature spectrum of high chemical reactivity is minimized. Such tooling is referred to as "chill" type.

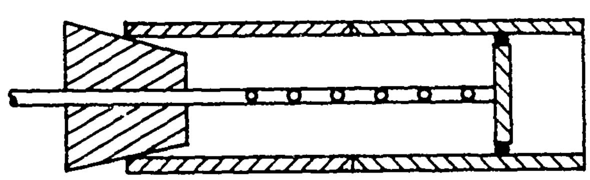
Tooling can be designed to contain and/or supply inert gas to help shield the access side of the weld area. A typica' example of such tooling is sketched in Figure 4-1.0.6-1. Similar concepts are used to protect the nonaccess (root) side of a weld joint. Figure 4-1.0.6-1 also illustrates several methods of preventing root contamination. Porous metal elements and baffle plates are often



Conventional Weld Tooling



Special Tooling for Titanium



Root Shielding of Tubing Joint

FIGURE 4-1.0.6-1. WELD TOOLING

used in special tooling to provide good gas coverage with minimum velocity flows. Advantage also is taken of the fact that argon tends to settle and displace air. Conversely, helium is best suited for displacing air when a rising gas flow is desirable.

4-1.0.7 Heat Input

The term "heat input" is widely used in the welding industry to characterize many of the conditions typical of fusion welding. Limiting heat inputs are defined by:

(1) The minimum energy required to melt sufficient metal to form a weld
(2) The maximum usable energy level that will produce an acceptable weld, or
(3) A maximum level that will not degrade properties of a particular material.

With titanium, it is best to use heat inputs just above the Condition 1 level above. Heat inputs above this level can only contribute to various bad effects. An exact measure of heat input is not readily made, but good empirical formulae are known for each welding process. Intraprocess comparisons of heat inputs are not always valid and should be viewed with caution. Also, the calculation of heat inputs for multiple-pass weldments does not present a truly representative picture.

Lowest heat inputs are obtained with electron-beam welding. Then, as a general rule, heat inputs typical of normal welding conditions increase as follows:

(1) Single-pass TIG -- no filler
(2) Single-pass TIG -- with filler
(3) Multipass TIG -- with filler
(4) Single-pass MIG
(5) Multipass MIG.

Other general trends useful in estimating heat input are:

(1) Welds made with helium shielding gas have a lower heat input than similar welds made with argon shielding

(2) Higher welding speeds result in lower heat inputs

(3) High currents or voltages result in high heat inputs (at any given speed)

(4) Small melted zones are characteristic of low heat inputs.

4-1.0.8 Shrinkage -- Distortion

Fusion-weld processes are characterized by thermal cycles that cause localized shrinkage. Often, this shrinkage in turn causes distortion of the parts being joined. Figure 4-1.0.8-1 illustrates the changes in shape that occur just as the result of welding a simple butt joint. More complex weldments obviously involve much more complex shrinkage and distortion patterns.

Weld shrinkage must be planned for, since there is no absolute way to avoid it. Thus, a knowledge of expected shrinkage values for typical weld configurations is needed before production welding applications. Also, a logical sequence of welding components involving several welds must be established with shrinkage in mind. With the proper welding sequence, shrinkage can be turned into good use to minimize distortion. This is accomplished by properly balancing the various shrinkage forces developed.

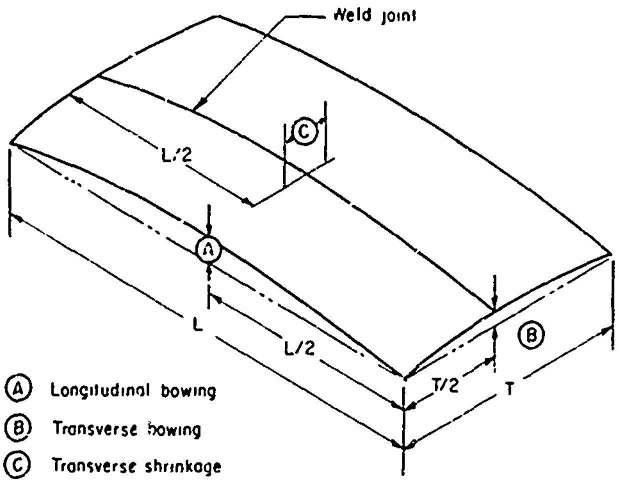


FIGURE 4-1.0.8-1. TYPES OF WELD-JOINT DISTORTION

Shrinkage also can be controlled to some extent by the restraint imposed by tooling. Use of this technique is sometimes helpful in preventing serious part distortion. (Caution: Freedom from distortion does not mean that a weldment is not highly stressed! Quite often the converse is true.)

Shrinkage and distortion are minimized by using low heat inputs. Thus, the listing given earlier also is valid for showing the relative tendencies of fusion-welding processes to produce these changes. Unnecessary weld reinforcement also is undesirable from the standpoint of keeping shrinkage and distortion as low as possible.

4-1.0.9 Residual Stress Distortion

Weld shrinkage inevitably leaves residual stresses in fusion weldments. Residual stresses are defined as those that exist in a body without any external force acting. The residual stresses in a welded joint are caused by the contraction of the weld metal and the plastic deformation produced in the base metal near the weld during welding. Residual stresses in a welded joint are classified as:

(1) "Residual welding stress", which occurs in a joint free from any external constraint

(2) "Reaction stress" or "locked-in stress", which are induced by an external constraint.

A typical distribution of residual stresses in a butt weld is shown in Figure 4-1.0.9-1. The stress components concerned are those parallel to the weld direction, designated σx and those transverse to the weld, designated σy. The distribution of the σx residual stress along a line

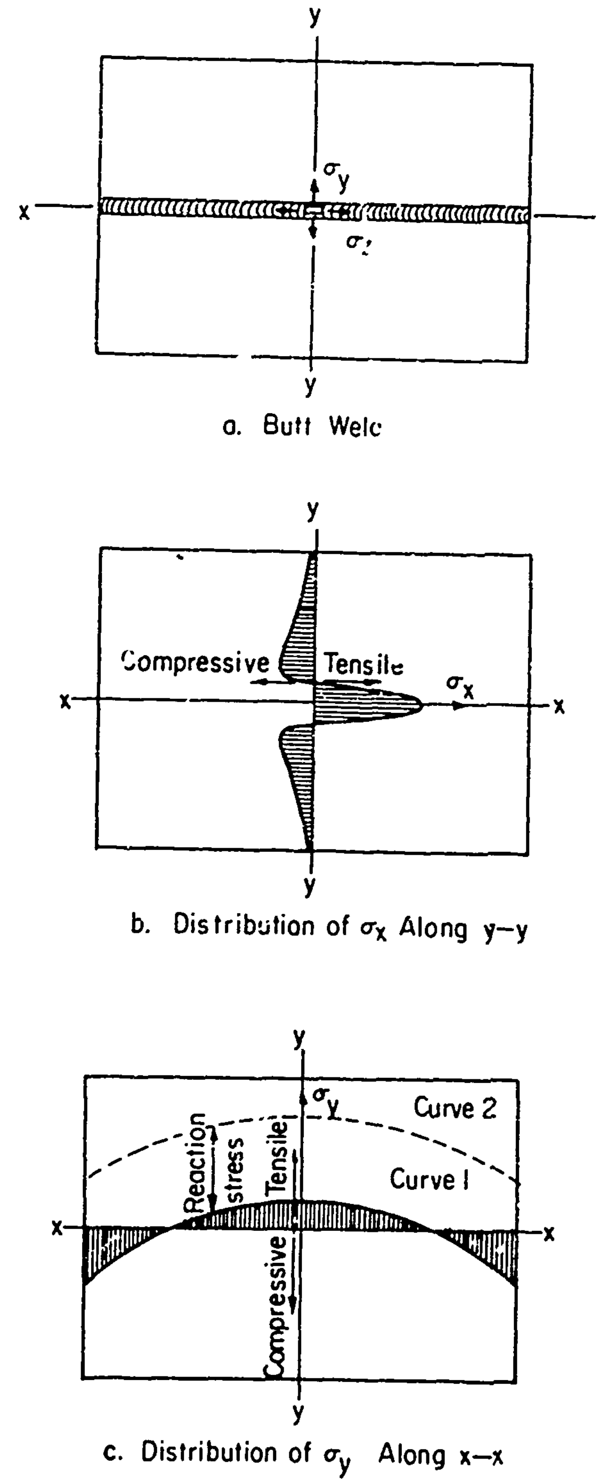


FIGURE 4-1.0.9-1. DISTRIBUTIONS OF RESIDUAL STRESSES IN BUTT WELD

transverse to the weld, y-y, is shown in the Figure 4-1.0.9-1b. Tensile stresses of high magnitude are produced in the region of the weld; these taper off rapidly and become compressive after a distance of several times in the width of the weld, then gradually approach zero as the distance from the weld increases.

The maximum residual stress in the weld is determined by:

(1) Expansion and contraction characteristics of the base metal and the weld metal during the welding thermal cycle

(2) Temperature versus yield strength relationships of the base metal and the weld metal.

Much research in mild-steel weldments has shown that the maximum stress is as high as the yield stress of the weld metal. However, in a recent investigation,[2] the maximum stresses in weldments made with heat-treated SAE 4340 steel were around 50,000 to 80,000 psi, considerably less than the yield strengths of the weld metal (around 150,000 psi) and the base metal (224,000 psi). In limited investigation on titanium-alloy weldments, maximum residual stresses ranging from 35,000 to 85,000 psi have been observed, depending upon the type of base metal and welding processes.[3-5] However, the effects of base-metal and weld-metal properties and welding processes on the magnitude of residual stresses in titanium-alloy weldments have not been established.

The distribution of σy residual stress along the length of the weld, x-x, is shown by Curve 1 in Figure 4-1.0.9-1c. Tensile stresses of relatively low magnitude are produced in the middle part of the joint, and compressive stresses are observed at the ends of the joint.

When the lateral contraction (contraction in y-y direction in Figure 4-1.0.9-1) is restrained by an external constraint, the distribution of σy is as shown by Curve 2 in Figure 4-1.0.9-1c. The difference between Curves 2 and 1 is the reaction stress. An external constraint has little influence on the distribution of σx residual stresses.

Residual stresses in the thickness direction (z direction) become significant in butt joints made with heavy plates, say over 1 inch thick. From the condition of equilibrium of stresses, residual stresses in the thickness direction must be zero on both surfaces of the plate. Consequently, the thickness-direction stresses are usually most significant in the mid-thickness regions.

4-1.0.10 Residual Stress Effects

For many years there was a trend among engineers to discount the effect of residual stress, since it had been proven that the effect or residual stress is almost negligible when a welded structure fails in a ductile manner. During the last several years, much information has been obtained on the effect of residual stress on brittle fracture in steel weldments. It has been found that residual stresses decrease the fracture strength of weldments only when certain conditions are satisfied, but that the loss of strength can be drastic when these conditions are satisfied. No systematic investigation has been made on the effects of residual stresses on fractures in titanium-alloy weldments. The following discussions are based on information on steel weldments and the limited data on titanium-alloy weldments.

In general, the effect of residual stress is significant on fractures that take place at low applied stresses. Observations that have been made on various types of fracture are as follows:

(1) Ductile fracture: Ductile fracture occurs at high stresses after general yielding. The effect of residual stress on fracture strength is negligible.

(2) Brittle fracture: When a notch is located in areas where high residual tensile stresses exist, brittle fracture can initiate from the notch at a low applied stress and then propagate through the weldment. Extensive research has been conducted during the last several years on the low-stress brittle fracture of steel weldments. No systematic investigations have been made on the low-stress brittle fracture of titanium-alloy weldments. Some failures have been observed which indicate that residual stresses may have caused premature failures in titanium-alloy weldments.

(3) Stress-corrosion cracking and hydrogen-induced cracking. Stress-corrosion cracking and hydrogen-induced cracking occur under low, applied stresses, even under no applied stress. Residual welding tensile stresses promote the cracking, while residual compressive stresses suppress the cracking.

(4) Fatigue fracture: The effect or residual stress on fatigue fracture is still a controversial subject.

(5) Buckling failure: It is known that residual compressive stresses in the base-metal regions around welds may decrease the buckling strength of welded columns and plates.

4-1.0.11 Residual Stress Relieving

As indicated in the preceding section, there are a number of reasons for reducing or relieving the residual stresses associated with welded joints. To repeat, it is probably necessary to relieve the residual stresses whenever a welded structure is: (1) manufactured to close dimensional tolerances; (2) complex and contains many stress risers; (3) subjected to dynamic loading; (4) subjected to low-temperature service; and

(5) subjected to service conditions that might promote stress corrosion.

Residual stresses can be relieved in two ways: (1) mechanical-stress-relieving treatments that involve subjecting the weldment to tensile loads of a certain stress level and then removing the load or (2) a thermal treatment (stress-relieving heat treatment) in which the weldment is heated to a temperature at which the yield strength is low.

Mechanical stress-relieving treatments take a variety of forms. These include tensile stretching, roll planishing, and peening. With any mechanical stress-relieving treatment, control of the process is difficult. In addition, the complete removal of residual stresses by mechanical techniques is difficult to accomplish. Mechanical stress-relieving techniques are most effective in accomplishing a redistribution of residual stresses in a single direction. Effective stress relieving by operations such as roll planishing requires that the weld geometry be very consistent prior to the planishing operation. Because of this and other inherent characteristics of roll planishing, this method of stress relieving is not expected to be very useful in controlling the residual stresses in joints for airframes.

Thermal stress-relieving treatments are commonly employed for many materials, including a number of titanium alloys. Thermal stress-relieving treatments can be combined quite effectively with hot sizing operations to control both the existing residual stresses and to produce parts to close dimensional tolerances. Thermal stress-relieving treatments produce much more uniform changes in the residual stress patterns than do mechanical stress-relieving treatments. For most titanium alloys, a treatment between 1000 and 1450 F for a period of time ranging from 1/2 to several hours is required for stress relieving. Possible interactions between a thermal stress-relieving treatment and other changes in a material that may affect its properties must be anticipated. For example, age hardening will occur in the 6Al-4V titanium alloy within the weld zone over a certain temperature range. If this age hardening is allowed to occur, it may reduce the beneficial effects of stress relieving. A similar effect is noted with the Ti-13V-11Cr-3Al alloy, although for different reasons. With this alloy, exposure to the normal stress-relieving temperature range will result in a drastic loss of bend ductility in the weld zone. Thus, it is necessary to find other methods of relieving the residual stresses in the alloy. This has been done by combining mechanical and thermal treatments to alter the residual stress patterns in the circumferential joints of rocket-motor cases.[5]

4-1.0.12 Inspection

Weldments produced by fusion processes are inspected for two reasons. First, it is often desirable or necessary to check changes in dimensions that may have resulted from welding. The visual and measurement-type inspections performed for this purpose may also include checks of weld-joint profile and measurements of the weld thickness. Second, various inspection procedures are used to ensure that the weldments produced are of satisfactory quality. The most commonly used techniques in this area include visual, dye-penetrant, and X-ray techniques. Various types of leak tests are also used on components designed to contain gases or fluids. Unfortunately, no suitable nondestructive inspection technique exists for detecting weld contamination of titanium weldments. Use is being made of indications based on surface discoloration during welding. However, the presence or absence of a discolored surface is not a reliable method of detecting contamination of titanium welds with interstitial elements.

The ease with which inspection can be accomplished varies with different joint geometries. Butt joints, T-joints, and corner joints are generally much easier to inspect than joints involving overlapping layers of material.

4-1.0.13 Specifications

Most of the materials and processes that will be used in titanium welding are covered by some type of specification. The basic specifications are generally MIL standards,[6,7] or other applicable Federal Government specifications. However, the most pertinent and important facets of titanium-joining technology are often not covered by these specifications. Therefore, most of the aerospace companies have developed company specifications, which are used in lieu of, or in the absence of, suitable Federal specifications.[8-10] These company specifications are almost always more restrictive and definitive than any comparable Government-type specification. This is probably because the company specifications are generally written with a more limited coverage in mind, than is the case with many Government specifications.

The lack of an adequate inspection method for determining weld contamination makes it necessary to place a high degree of reliance on process specifications for fusion-welding processes. Such specifications should spell out in some detail the requirements for preweld cleaning and for ensuring that all welds are adequately protected during the welding operation to prevent contamination.

4-1.0.14 Defects

The definition of fusion-weld defects is arbitrary. Although many years of experience have been gained with welding codes and specifications that either prohibit or allow certain features characterized as defects, very little of this experience is based on statistically sound engineering data. As a result, features recognized as defects are generally limited in accordance with very conservative practices. This approach to defects has been quite successful in the past, but is of some concern when dealing with many of the newer materials being used in various types of fabrication. This concern is based on the belief that the removal of certain types of features classified as nonallowable defects often results in more damage to the serviceability of a structure than the damage that potentially might have been done by allowing the feature to remain. The reluctance of many welding engineers to repair certain features is based on this feeling, not on a desire to make the welding job easier.

Typical fusion-weld features that are sometimes classified as defects are shown in Figure 4-1.0.14-1.

The fabrication of defect-free welds is highly dependent on the quality requirements of applicable specifications and on the inspection methods that are used. For example, hardly any welding codes or specifications allow cracks in a weld. However, cracked welds can and do get into service if inspection methods that will insure detection of all cracks present in a weld are not required.

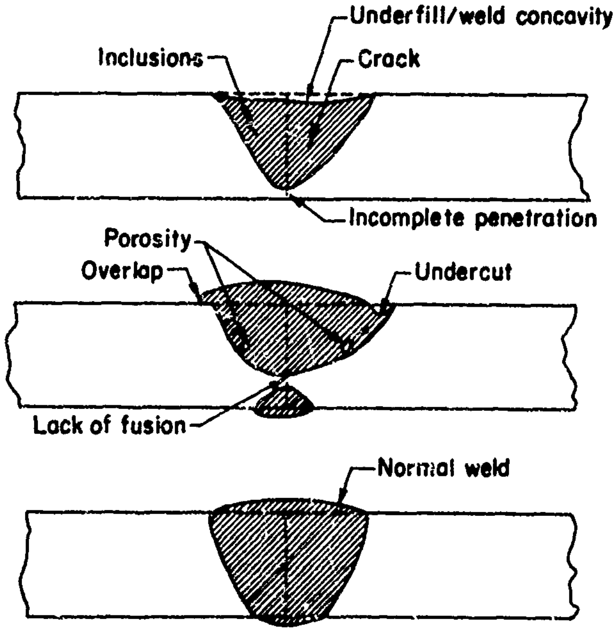


FIGURE 4-1.0.14-1. FUSION-WELD DEFECTS

The only reliable way to determine what weld features are truly defects is to evaluate the effects of such features in a test program. Such an evaluation must include tests that are representative of the service conditions. Many defect-like weld features have no effect on the static-tension properties of the weld. However, these same features may be found to seriously degrade performance in a fatigue test.

With the knowledge currently available about the performance of titanium-fusion weldments, a conservative engineering approach to defects should be followed. Because of the prevalence of porosity in titanium-fusion weldments, it would be desirable to determine more realistically the extent to which porosity can be allowed, or develop simpler means of minimizing porosity than those currently available.

4-1.0.14.1 Porosity

The prevalence of porosity problems in titanium welding warrants special mention. A special report on this subject is available as DMIC Memorandum 194. The Summary from this report is repeated here:

"Porosity in fusion welds in titanium has been encountered to some extent in all programs using this joining method. While measures to control cleanliness and to employ good welding techniques have successfully reduced the occurrence of porosity, specific identification of the various causes of porosity is still lacking.

"Some factors suspected of causing porosity in titanium welds are:

(1) Hydrogen. Many of the things which when eliminated reduce porosity are sources of hydrogen.

(2) Cleanliness of Joint Area. Mechanical cleaning of edges to be welded and adjacent surfaces reduces porosity and improves uniformity of welds. Two factors shown to increase porosity are fingerprints and handling with dirty rags or lint-bearing gloves. Plasticizers dissolved from rubber gloves by solvents, especially alcohol, have been identified as a cause of porosity. "Soapy" residue in cloths used for wiping cleaned joint areas also has been identified as a cause of porosity.

(3) Contamination in Filler Wire. Surface inclusions worked into the filler wire during drawing have been identified as a major cause of porosity.

(4) Welding Procedures and Techniques. There is evidence that some of the parameters associated with welding procedures also affect porosity. Many of these are interrelated and the offending parameters are not well identified; however, improper technique in tack welding and wide joint gaps in fusion welding have been identified as causes of porosity. Other parameters that play a part in causing porosity are rates of heat input, rates of cooling, welding speeds, arc voltage, and rates of gas flow."

Anyone encountering porosity problems should obtain this report, as it contains a good summary of published information on the subject.

Unpublished data generally confirm the DMIC summary.[11] In addition, data showing the effects of edge preparation, pickling, preheat, and welding variables on porosity formation are available.

Porosity in titanium welds can be controlled if the procedures that have been developed by the many investigations in the area are followed.

4-1.0.15 Repairs

As mentioned in the preceding section, repair of fusion weldments is not desirable. However, it is an almost inevitable occurrence in production operations. Perhaps the most important aspect of repair welding is determining what caused the defect that must be repaired. With titanium, this is important, not only for its feedback value to minimize the need for subsequent repairs, but also to determine a suitable repair-welding procedure.

Cracks, which occur rarely in titanium-fusion weldments, are generally the result of contamination from some external source. For example, copper may get into a weld if the equipment malfunctions during MIG welding. To effect a successful repair, the material contaminating the titanium must be removed first. Fusion welds that are contaminated as a result of poor shielding may require complete removal of the first weld made and its replacement.

Whenever practical, the welding fixtures and process used on the original weld should be used for the repair. When this is not possible, it is common practice to use manual TIG welding for repair operations. The shielding precautions used in the original welding procedure should be used for all exposed surfaces of the weldment. Porosity can often be reduced to an acceptable level by remelting a weld under the same conditions originally used to make the joint.

4-1.1 TIG WELDING

TIG welding is used extensively for joining titanium alloys and many other high-quality materials. TIG welding can be done manually, semiautomatically, or fully automatically. TIG welding is particularly suited for joining of very thin materials. It can, however, be used on almost any thickness, but as the thickness increases above about 0.12 inch other fusion-welding processes may be more applicable.

In TIG welding, all of the heat required to melt the joint edges is supplied by an arc between a tungsten electrode in the welding torch and the workpiece. The arc and surrounding area is kept free of air by a flow of inert gas around the tungsten electrode. TIG welds are often made in which only the edges of the parts to be joined are melted. Sometimes, additional metal is added to the weld by using a filler wire. Filler wire is always added when the joint contains a groove or similar preparation. The addition of filler wire to joints that are not grooved (square-butt joints) increases the tolerance of TIG welding for slight variations in the joint fitup. This can be quite important in welding titanium, since the metal is very fluid when melted.

Most TIG welding of titanium has been done in the flat welding position. Other welding positions have been used to a limited extent. When welding titanium in other positions, the changes in shielding-gas behavior should be anticipated. Welds made in the horizontal position would be expected to be slightly more prone to porosity entrapment than welds made in other positions. Vertical welding may have advantages in the fabrication of airframe components.

4-1.1.0 Equipment

Conventional TIG welding power supplies, torches, and control systems are used effectively in welding titanium. No significant changes in welding characteristics or weld properties have been reported that can be attributed to the use of any specific type of welding equipment. The conventional TIG welding equipment selected for use must be supplemented with auxiliary shielding devices.

Several types of shielding chambers have been used to weld titanium and other reactive metals. Such chambers are designed to contain the entire component to be welded, or in some cases, merely the weld-joint area. The air in the chamber is replaced with inert gas by (1) evacuation and backfilling, (2) flow purging, or (3) collapsing the chamber and refilling with inert gas. Welding chambers are particularly useful in the welding of complex components that would be difficult to fixture and protect properly in the

air. Use of a welding chamber, however, is not a cure-all. The inert gas in many welding chambers is of much poorer quality than the inert gas contained in the conventional flowing shields. Leakage of air or water vapor into a chamber atmosphere must be avoided to do a good job in welding titanium. Monitor devices that will disclose contamination of a chamber atmosphere are available.

Titanium alloys also can be welded very successfully in air with the right supplemental equipment. The inert gas flowing from a conventional TIG welding torch is generally not sufficient to protect titanium during welding. Auxiliary trailing shields attached to the welding torch, or auxiliary shielding devices built into the weld tooling afford the required protection. The importance of tooling to assist in weld shielding was discussed in Paragraph 4-1.0.6. Figure 4-1.1.0-1 shows a commonly used type of trailing shield. Such shields are designed to supply a uniform nonturbulent flow of inert gas over the weld as it cools behind the torch. It is much easier to ensure good shielding during mechanized TIG welding than in manual operations. Mechanized welding operations are certainly recommended and are used wherever possible in welding titanium assemblies for this and many other reasons.

Direct-current straight polarity is normally used in TIG welding of titanium.

Use has also been made of back-up flux[12] to protect the underside of the joint during arc welding, thus eliminating the need for reverse-side shielding gas. The nonreactive flux, applied as a paste, powder, or tape, fuses on heating and subsequently volatilizes to seal the weld from the atmosphere.

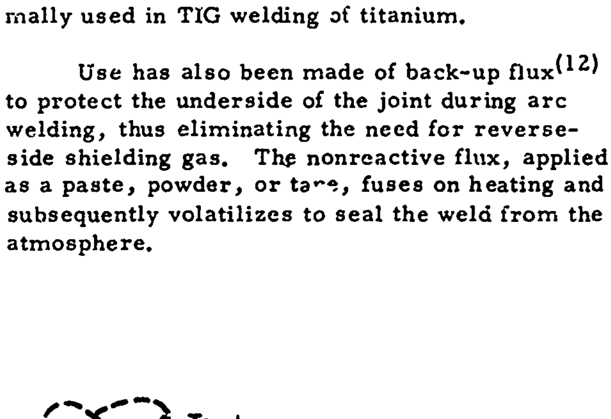


FIGURE 4-1.1.0-1. TRAILING SHIELD

4-1.1.1 Materials

The materials used in TIG welding do not differ markedly from those used in other fusion-welding processes. For welds of very short length, cut and straightened lengths of filler wire may be used instead of continuous coils. Cut lengths are easier to clean immediately prior to welding than coiled products. In manual TIG welding, sheared strips of base-metal sheet are sometimes used as filler wire. On rare occasions, a similar procedure is used in mechanized welding when a preplaced strip of sheet is inserted in the joint to serve as a filler metal. This procedure is not recommended for titanium because of the difficult handling and potential contamination problems involved.

4-1.1.2 Welding Conditions

Welding conditions are dependent on material thickness, joint design, the type of weld tooling being used, and whether manual or machine welds are made. Also, for any given thickness and joint design, various combinations of amperage, voltage, welding speed, and filler-wire input speed are satisfactory. As a result, no hard and fast rules can be specified for welding conditions. Pertinent comments that are related to welding conditions appear in Paragraph 4-1.0.5, Inert Gas; Paragraph 4-1.0.7, Heat Input; Paragraph 4-1.0.8, Shrinkage -- Distortion; and Paragraph 4-1.0.14, Defects. Table 4-1.1.2-1 illustrates typical welding conditions that have been used in the TIG welding of titanium.

Welding conditions generally do not have to be adjusted radically to accommodate the various titanium alloys. Welding conditions are often adjusted as a means of controlling weld porosity. Almost any change in a welding condition whose net result is to decrease the freezing rate of the weld will produce a decrease in porosity. Such changes are not consistent with good shielding practice, but sometimes they must be used.

4-1.1.3 Properties

A large number of joint tests have been made on TIG welds in the titanium alloys of interest. A complete analysis of this data has not been possible during this program.* Sources of TIG weld data are listed in Table 4-1.1.3-1.

The properties measured by static tension, notch tension, bend and crack susceptibility tests, compare very favorably with parent-metal properties. Axial tension fatigue tests generally show

*Most test data are from specimens welded without filler metal and which have not been stress relieved. Considering this and the general problems in projecting data from small specimens, a detailed analysis may not be warranted.

TABLE 4-1.1.2-1. TIG WELDING CONDITIONS FOR VARIOUS ALLOYS

Material Thickness, inch	Travel Speed, ipm	Current, amp	Arc Voltage, volts	Filler Wire Diameter, inch	Filler Wire Speed, inch	Flow Rate, cfh, and Gas	Reference
0.008	16	10	14	--	--	11He	--
0.02	5-1/8	27	--	0.03	7.7	7A, 5He	13
0.03	10	30	10	--	--	15A	--
0.04	14	30	20	0.032	18	30He	17
0.05	Manual	65	9	--	--	10A	21
0.05[a]	7	60	9	--	--	20A	14
0.05[a]	6	60	9.3	--	--	18A	14
0.06	10	95	10	--	--	15A	21
0.06	12	125	10	0.062	22	15A	21
0.07	Manual	90	9	--	--	15A	21
0.08	Manual	125	9	--	--	15A	21
0.09	10	195	12	--	--	20A	21
0.09	12	210	12	0.062	22	20A	21
0.125	12	230	12	0.062	20	20A	21
0.125[a]	15	180	18	--	--	Chamber He	15
0.125[a]	8	110	18	--	--	Chamber He	15
0.140	4.5	165	13	0.047	26	40He	5
0.20[a]	6	205	12	--	--	50He	14
0.20[a]	4	205	14	--	--	40He	14

(a) Two-pass procedure.

a significant decrease in properties compared to similar parent metal specimens. Fracture-toughness test results on fusion weldments are not easily interpreted. Depending on the evaluation criteria selected, the data from these tests are indicative of fair to good performance. Weldment thermal stability trends in the 8Al-1Mo-1V and 6Al-4V alloys appear to parallel parent-metal trends.

TIG weldments have been used in several structural test components. The behavior of weldments in such tests is by far the best evaluation of joint properties. Reported behavior to date is encouraging, with few exceptions. Delayed cracking of weldments has been observed in some instances. In some cases, the reasons have been apparent and solutions obvious. Where the cause of such cracking is not known, a strong effort to find the cause is indicated.

4-1.2 MIG WELDING

MIG welding is being developed for joining titanium alloys and has been used to a somewhat lesser degree than TIG welding for actual production components. MIG welding can be semiautomatic or fully automatic. MIG welding is particularly well suited for the joining of thicker sections of titanium. The process is very economical for this type of work because high weld-finishing rates are obtainable. However, MIG welding can be used for material with thicknesses down to about 1/8 inch.

In MIG welding, the heat required to melt the joint edges is supplied by an arc between a consumable metal electrode in the welding torch and the workpiece. For welding of titanium, the consumable electrode is either commercially pure-titanium wire or a titanium-alloy wire. The arc and surrounding area are kept free of air by a flow of inert gas around the electrode, as in TIG welding. All of the metal added to the weld joint is supplied by the consumable electrode. This metal is transferred from the electrode to the workpiece as fine droplets or metal spray. The metal being transferred across the arc may be exposed to much higher temperatures than if it were just being melted. The combination of very high temperatures and fine particle sizes represents a set of conditions ideal for the contamination of titanium. Therefore, in MIG welding, it is extremely important that the arc area be completely protected from exposure to any gases other than the inert gases.

4-1.2.0 Equipment

Conventional MIG welding power supplies, torches, and control systems are used effectively in welding titanium. The nature of MIG welding makes this process somewhat more sensitive to changes in welding-equipment characteristics than is the case for TIG welding. The limited published information on MIG welding[21,34-37] indicates that constant potential power sources are being used with various types of constant wire feeders. Conventional MIG welding torches are modified

TABLE 4-1.1.3-1. TIG WELD PROPERTY DATA SOURCES

Base Alloy[a]	Filler Alloy	Test Condition[b]	Thickness, in.	Type of Tests and Test Temperature, F	Reference
D	D	A	0.187/0.250	Static tension (RT) and bend (RT)	13
B	D	A	0.02/0.09	Static tension (RT) and bend (RT)	13
B	B	A	0.032	Static tension (RT) and bend (RT)	13
B,D	--	A	0.050	Static tension, notched tension (K_t=3), fracture toughness, and fatigue (-110, 75, 400, 650); bend (RT)	14
B,D	--	A	0.20	Same as above except static tension at 75 and 650 only; add thermal stability	14
B	A,B	D	0.125	Bend (RT) Charpy V notch impact (-40 to 65 C)	15
E	E	A	0.125	Bend (RT) Charpy V notch impact (-40 to 65 C)	15
F	A	D,E,F	0.140	Static tension and bend (RT)	5
E	E	A	0.125	Static tension and notched tension (K_t=8) (-40, 70, 200, 400)	5
E	E	A,D	0.125	Fracture toughness, bend, biaxial stress (RT)	5
E	A	A,D	0.125	Static tension, notched tension (K_t=8), bend, and fracture toughness (RT)	5
E	A,D	D	0.14	Cyclic loading (RT)	5
B	A	E	0.18	Cyclic loading (RT)	5
E	E	A	0.14	Hydrostatic burst (RT)	5
E	E	(c)	0.14	Static tension, fracture toughness, cyclic loading (RT), and hydrostatic burst	5
E	E	A,C,D	0.1	Static tension, notched tension (K_t=16), and bend (RT)	16
E	(d)	D,E	0.04	Static tension and bend (RT)	17
B	(d)	D,E	0.04	Static tension and bend (RT)	17
B	A	B	0.06(?)	Static tension (RT)	18
B	A, none	A,D	0.025	Bend (RT)	19
D	--	A	0.02, 0.09	Static tension and thermal stability (RT, 600, 800, 1000), bend (RT)	20
A,B,C,D,E	Data from before 1960				21
D	--	--	0.02 to 2	Comprehensive evaluations	1
D	--	A	0.032, 0.06	Static tension, notched tension (K_t=16) (RT, 600)	22
			0.071	Thermal stability (RT, 600, 800, 1000); thermal-stress stability (RT)	
D	--	A	0.062	Static tension (-320, -110, -65, RT, 800, 1000), bend test (RT), creep stability (RT), and notched tension (K_t=3 and 6) (-320, -110, and -65, RT)	23
D	--	B	0.062	Static tension (RT)	23
B	--	A	--	Static tension (RT to 800)	24
B	--	G	--	Static tension (RT to 800)	24
D	--	A		Static tension (RT to 800)	24
B,D	--	--	--	Fatigue (RT)	24
B	A,B,C	B	0.060	Static tension, longitudinal and transverse	25
B	A,B,C	F	0.060	Static tension, longitudinal and transverse	25
B	A,B,C	B	0.250	Static tension, longitudinal and transverse	25
D	D	A	0.045, 0.090	Static tension (RT and ET)	26
F	A,C,D,F	A	0.040, 0.080	Static tension (RT)	26
C	A	A	0.125-0.250	Static tension, bending fatigue	27
G	A[e]	C	0.125	Static tension,(RT), bend (RT), impact	28
G	B[e]	C,G	0.125	Static tension (RT), bend (RT), impact	28
G	A	D	0.125	Bend (RT), Charpy V notch impact (-40 to 65 C)	15
G	G	A,C	0.090	Bend (RT), static tension	29
G	Various	C,D	0.040	Bend (RT)	30
G	A	C	0.125	Longitudinal and transverse static tension (RT), fracture toughness	31
G	--	C,D	0.063	Longitudinal and transverse static tension (-320 to 80 F)	32
H	--	A,B,C	0.040	Static tension (RT and 600 F), notched tensile, creep stability	33
H	A	C	0.08	Static tension (RT), notched tensile)	33
H	6Al-2Mo	C	0.08	Static tension (RT), notched tensile)	33

(a) A = cp Ti, B = 6Al-4V, C = 5Al-2.5Sn, D = 8Al-1Mo-1V, E = 13V-11Cr-3Al, F = 6Al-6V-2Sn, G = 4Al-3Mo-1V, H = 6Al-2Sn-4Zr-2Mo.

(b) A = annealed, as welded; B = welded, stress relieved; C = annealed, welded, aged; D = aged, welded; E = aged, welded, aged; F = aged, welded, annealed; G = annealed, welded, annealed, aged.

(c) After special postweld hot rolling to relieve residual stresses.

(d) Nine different filler alloys used.

(e) Various other filler wires.

to provide the necessary supplemental gas shielding needed for titanium. Although MIG welding has been conducted in vacuum-purged weld chambers, it is likely that most applications of this process will be set up in air.

For in-air welding with the MIG process, supplemental shielding devices similar to those described in Paragraph 4-1. 1. 0 for TIG welding, should be employed. Trailing shields designed for MIG welding are usually considerably longer than those used in TIG welding. This is to ensure good protection for the larger volumes of material that are heated during MIG welding and that cool slower.

Direct-current reverse polarity is normally used in MIG welding of titanium.

4-1. 2. 1 Materials

MIG welding is a process highly dependent on obtaining good materials. The most important material in MIG welding is the welding electrode or filler wire. MIG welding makes use of wire provided in coil form. Other methods of supplying wire are impractical for MIG welding. The quality requirements for MIG welding wire are perhaps even more stringent than comparable requirements for TIG wire. One reaon for this is that the current flowing in the welding arc must be transferred from a contact or guide tube to the wire just above the point at which the arc is burning. A very uniform wire size (diameter) is important to effecting good current transfer into the arc. Also, the wire-feed speeds employed in MIG welding are much higher than those employed in TIG welding. Therefore, any wire characteristic that tends to impede the flow of wire through the welding torch may cause an undesirable variation in welding conditions or even an equipment malfunction. Such undesirable characteristics as kinks, soft spots, and rough surfaces are not tolerable in MIG welding wire.

4-1. 2. 2 Welding Conditions

The welding conditions employed in MIG welding are dependent on two separate groups of factors. First, a suitable combination of current and voltage must be selected that will produce the desired arc characteristics. The arc stability and metal transfer occurring in a MIG arc are very dependent on these electrical variables and the composition of the shielding gas used. At low current densities (current divided by the cross-sectional area of the electrode wire), metal transfer is erratic and consists of large metal particles. As the current density is increased arc stability is improved and metal transfer changes to a characteristic spray-type transfer. High-current-density welding conditions are generally preferred in the MIG welding of most materials. The second group of factors affecting the welding conditions are the material thickness, joint design, weld tooling, and whether manual or machine welding techniques are being used. The first group of factors affecting welding conditions usually set minimum limits on the usable current and voltage. Variation above these minimums combined with the possible variations introduced by the second group of factors make it possible to produce welds of very similar appearance with many possible combinations of welding conditions. Table 4-1. 2. 2-1 illustrates some of the combinations that have been used in the MIG welding of titanium and its alloys by various investigators. Insufficient work has been reported on MIG welding to allow any comment on the most suitable conditions of those that have been investigated.

4-1. 2. 3 Properties

The sources of property data for MIG welds are shown in Table 4-1. 2. 3-1. Only smooth and notched tension and Charpy V notch impact data are available. Satisfactory properties are generally obtained in alpha or alpha-beta alloys. Very low impact properties are obtained in the beta alloy.

Cracking during or after welding has been reported in connection with MIG welding of thick titanium plates in some alloys.

4-1. 3 ELECTRON-BEAM WELDING

Electron-beam welding is an extremely attractive process for use in joining titanium and other highly reactive materials. One major advantage of the process is that all welding occurs in a high-vacuum chamber. Contamination of the weldment from external sources is essentially nonexistent during electron-beam welding. All electron-beam welding is done with mechanized equipment. Electron-beam welding is applicable to all of the thicknesses that might be involved in the airframe structure of large or high-performance aircraft up to about 2 inches. Electron-beam welds made with high-power-density-type equipment exhibit a characteristic high depth-to-width ratio of the weld metal and heat-affected zone. This characteristic is advantageous from the standpoint of minimizing the distortion that normally accompanies welding. It may also result in welds whose properties are not altered significantly from those of the base material.

In electron-beam welding, the heat required to melt the joint edges is supplied by an electron beam generated in an electron gun. This beam is focused and accelerated so that it strikes the joint line parallel to the existing interface. Electron-beam welds are usually made without the addition of any filler wire. In very thick material, the first pass made to completely penetrate the joint sometimes is undercut along both edges of the weld metal. This undercutting can be minimized by a

TABLE 4-1.2.2-1. MIG WELDING CONDITIONS FOR VARIOUS ALLOYS

Material Thickness, inch	Travel Speed, ipm	Current, amp	Arc Voltage, volts	Electrode Diameter, inch	Electrode Speed, ipm	Tip to Work Distance, inch	Flow Rate, cfh, and Gas	Reference
0.125	15	250/260	20	0.062	200/225	--	50A, 15He	21
0.250	15	300/320	30	0.062	300/320	--	50A, 15He	21
0.375	25	350/360	33	0.045	865	0.6[(a)]	20A, 100He	1
0.500	15	340/360	40	0.062	375/400	--	50A, 15He	21
0.625	15	350/370	45	0.062	400/425	--	50A, 15He	21
0.625[(b)]	Manual	300/320	38	0.062	--	--	36A, 10He	36
0.71	7.2	340/345	31/32	0.08	340	--	A, He	28
1.0[(b)]	20	320/330	37	0.062	380	1.2	70A	35
1.0[(b)]	23	340/350	36	0.062	380	1.2	70A	35
2.0[(b)]	Manual	300/320	38	0.062	--	--	36A, 10He	36
2.0[(b)]	20	330/340	33	0.062	450	0.750/1.12	Chamber A	34
2.0[(b)]	30	315/325	33	0.062	450	0.875	Chamber A	34

(a) 8-degree leading angle.
(b) Multipass procedures.

TABLE 4-1.2.3-1. MIG WELD-PROPERTY DATA SOURCES[(a)]

Base[(b)] Alloy	Filler Alloy	Properties Reported and Temperature Range: Thickness, inch	Static Tension[(c)]	Notched Tension[(c)]	Charpy V Notch	Other	Reference
A,B,C	Various	--	Data from before 1960				21
A	A and B	2	RT	--	-80 to +80	--	34
C	A,B,C	2	RT	--	-80 to +80	--	34
E	E	2	RT	--	-80 to +80	--	34
B	A and B	2	RT	--	-80 to +80	--	34
B	A,B,C	1	RT	RT (K_t=3.9)	-300 to 150	Flat tension	35
B	A and B	2	RT	--	--	--	36
B	B	0.500	RT	--	--	--	25
D	A	0.870	RT	--	--	--	25
G	Various	0.250	RT	--	--	Bend, impact	28
C[(d)]	C	0.560	RT	--	--	--	38
C[(d)]	C	--	--	--	--	Fracture toughness (-320 to 580 F)	38
G	A	0.125	RT	--	--	--	31
G[(e)]	A	0.125	RT	--	--	Fracture toughness (-200 to 800 F)	31
G[(f)]	A	0.125	RT	--	--	Fracture toughness (-200 to 800 F)	31

(a) Annealed, as welded.
(b) A = cp Ti, B = 6Al-4V, C = 5Al-2.5Sn, D = 8Al-1Mo-1V, E = 13V-11Cr-3Al, G = 4Al-3Mo-1V.
(c) 0.505 round specimens.
(d) Using back-up flux.
(e) Annealed, welded, aged.
(f) Aged, welded.

second weld pass made at somewhat lower energy levels with a slightly defocused beam, or eliminated by addition of filler metal through cold-wire feed or scab overlay. The underside of electron-beam welds also may exhibit an undesirable contour. Some type of metal-removal operation is generally required to produce an acceptable underside contour.

The flat welding position is generally used in electron-beam welding. The welding positions that can be used are limited by the versatility of the available welding equipment. Obtaining good shielding is not a factor affecting the selection of the welding position during electron-beam welding.

4-1.3.0 Equipment

Any type of electron-beam welding unit can be used effectively for welding titanium. Units that characteristically produce a low-power-density beam will not produce the high depth-to-width type weld that can be produced on high-power-density equipment. However, acceptable welds can be made with either type of equipment. Special electron-beam units using either clamp-on type chambers of special electron gun assemblies designed to allow the electron beam to be projected into the air have not seen much use on titanium. Clamp-on type chambers may be quite useful in the joining of long lengths of special shapes fabricated from titanium. It is expected that the welding of components of high-speed aircraft will make use of portable, local high-vacuum chambers as well as standard high-vacuum-equipment units.

4-1.3.1 Materials

No special material requirements are involved in electron-beam welding. However, because of the very high solidification rates associated with most electron-beam welding, it is imperative that the weld area of the parts to be joined be very clean prior to welding. The high freezing rates associated with electron-beam welding allow very little time for the escape of any gaseous impurities during welding. Thus, it is possible that electron-beam welds are somewhat more prone to porosity formation than other types of fusion welds. To date there is very little evidence either to substantiate or refute this.

4-1.3.2 Welding Conditions

The welding conditions used in electron-beam welding are dependent on material thickness and the type of electron gun being used. For a given thickness of material, various combinations of accelerating voltage, beam current, and travel speed are satisfactory. In electron-beam welding, the electrical parameters do not adequately describe the heat-input characteristics of the beam, since these characteristics are affected significantly by the focus of the beam. Measurements of beam diameter are difficult to make under production conditions, so that the transfer of welding parameters between different equipment units is very difficult. Fortunately, suitable welding parameters can generally be developed on a given piece of equipment with only a very few trials. Table 4-1.3.2-1 shows some of the welding conditions that have been used in the electron-beam welding of titanium and its alloys.

4-1.3.3 Properties

Sources of property data on electron-beam welds are shown in Table 4-1.3.3-1. In general, the properties obtained in electron-beam welds are very similar to those obtained in TIG welds.

4-1.4 ARC-SPOT WELDING

Arc-spot welding is being developed for joining titanium alloys in applications where resistance spot welding cannot be used or as an alternative to the resistance spot-welding process. Arc-spot welding can employ either the basic TIG or MIG welding process and will probably be a fully automatic technique. Arc-spot welding can be used to join thickness combinations that are not suitable for resistance spot welding and in joints which are accessible from one side only. TIG arc-spot welding will probably find its major use in the joining of overlapped material whose total thickness does not exceed 1/4 inch. MIG arc-spot welding will be used on thicker gages, up to a maximum of about 2 inches.

The major difference between arc-spot welding and either conventional TIG or MIG welding is that there is no relative lateral movement between the welding torch and the parts being joined. Starting and stopping cycles for the welding process are extremely important in arc-spot welding. The total welding time generally is quite short, so that it is necessary to automatically program welding parameters to insure a smooth start and stop of the process. The shielding of arc-spot welds is somewhat simpler than for conventional TIG or MIG welds. Simple cylindrical auxiliary shields placed around the welding torch are sufficient to prevent contamination from the top surface of the weld. Shielding of the underside of the joint may not be required unless a full-penetration weld is being made. If welds are full penetration, suitable root shielding also must be provided.

4-1.4.0 Equipment

The equipment required for arc-spot welding is generally similar to conventional TIG or MIG welding equipment. However, some means of programming appropriate welding parameters to obtain desired starting and stopping cycles must be available. For welding thicker gages of material, a means of retracting either the welding electrode or the weld contact tube must be a part of the equipment.

TABLE 4-1.3.2-1. ELECTRON-BEAM-WELDING CONDITIONS

Base Alloy	Thickness, inch	Acceleration Voltage, kv	Beam Current, ma	Travel Speed, ipm	Beam Diameter, inch	Reference
6Al-4V	0.05	85	4	60	0.006	14
6Al-4V	0.2	125	8	18	0.01	14
6Al-4V	0.191	28.2	170	98	--	Trade Lit.
6Al-4V	1.0	23	300	15	--	29
6Al-4V	1.75	55	360	40	--	29
Several	0.084/0.125	14	250	8 to 10	--	41
5Al-2.5Sn	0.09	90	4.8	18	--	39
13V-11Cr-3Al	0.125	135	6.5	28	--	39
13V-11Cr-3Al	0.125	20	95	30	--	Trade Lit.
13V-11Cr-3Al	0.03	30	26	89	--	14
8Al-1Mo-1V	0.05	110	2	45	0.005	14
8Al-1Mo-1V	0.2	120	8	20	0.006[a]	44
8Al-1Mo-1V	0.4	26	400	34	--	44
8Al-1Mo-1V	0.4	21	400	36	--	44
8Al-1Mo-1V	0.3	22	300	34	--	44
8Al-1M -1V	1	30	300	52	--	Hamilton Standard
Commercially Pure Ti	0.01	80	1	30	--	Hamilton Standard
Commercially Pure Ti	0.05	95	1.8	30	--	Trade Lit.
Commercially Pure Ti	0.125	125	6	30	--	Trade Lit.
Commercially Pure Ti	0.250	138	10	25	--	Trade Lit.
Commercially Pure Ti	0.340	150	15	60	--	Trade Lit.
4Al-3Mo-1V	0.084 to 0.125	14	250	8 to 10	--	45

(a) Oscillation = 0.2 inch.

TABLE 4-1.3.3-1. ELECTRON-BEAM-WELD-PROPERTY DATA SOURCES

Base Alloy[a]	Test Condition[b]	Thickness, inch	Type of Tests and Test Temperature, F	Reference
B and D	A	0.05, 0.20	Static tension, notched tension (K_t=3), and fracture toughness (RT); fatigue (75 and 650)	14
E	D	0.05, 0.1, 0.15	Static tension, notched tension (K_t=8), bend, and fracture toughness (RT); cyclic loading test (RT)	5
E	A and C	0.125	Static tension (RT)	39
E	C	0.125	Static tension (RT)	40
B,C,E	--	0.125	Static tension (RT), sheet impact (-200 to +300)	41
B and C	A	2	Static tension (RT)	42
B	D and E	1	Static tension and fracture toughness (RT)	42
B,D,F	A	--	Static tension (-110, RT, 500), bend (RT)	44
B,D	--	--	Fatigue (RT)	24
B	A	0.5	Fracture toughness, delayed fracture	24
B	A	0.050	Transverse tension (RT)	25
B	A	0.155	Transverse tension (RT)	25
D	A	0.045, 0.090	Static tension (RT)	26
F	A	0.080	Static tension (RT)	26
B	A,C,D, E[c]	1.0	Static tension, notch hardness, stress rupture (850 F)	29
B	E	1.75	Static tension, notch hardness	29
G	--	--	Static tension (RT), impact strength (-200 to 300 F)	45

(a) B = 6Al-4V, C = 5Al-2.5Sn, D = 8Al-1 Mo-1V, E = 13V-11Cr-3Al, F = 6Al-6V-2Sn, G = 4Al-3Mo-1V.
(b) A = annealed, as welded; C = annealed, welded, aged; D = aged, welded; E = aged, welded, aged.
(c) Single and two pass.

4-1.4.1 Materials

The materials used in arc-spot welding do not differ significantly from those used in either TIG or MIG welding. Sections 4-1.1.1 and 4-1.2.1 should be consulted for comments on materials.

4-1.4.2 Welding Conditions

The welding conditions employed in arc-spot welding are generally similar to the TIG or MIG welding conditions used in joining comparable thicknesses of materials. Welding conditions for the arc-spot welding of titanium have not been reported.

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4-2 Resistance Welding Processes

4-2.0 INTRODUCTION

Resistance welding is used to categorize welding processes in which joining is accomplished by heating to the melting point or very close to it, using heat generated by the resistance of the parts being joined to the flow of electric current. The most pertinent processes of this type are spot, roll-spot, and seam welding. In these processes, current is passed through a localized area of overlapping sheets until sufficient heat is generated to join the overlapped area. In conventional resistance welding, sufficient heat is supplied to melt a portion of the two sheets to form a weld nugget. This nugget is entirely contained within the remaining solid portions of the sheet. The size of the weld nugget can be controlled by selection of suitable welding parameters. Terminology similar to that used in fusion welding also is used in resistance welding. Any metal that is melted is called the weld metal or weld nugget. Metal around the joint that has been changed in some way by the heat involved is termed heat affected.

Resistance-welding techniques may also be used to make joints in which no melting is involved. Such joints may be called diffusion bonded, yield-point diffusion bonded, or solid-state bonded. Joints of this type are very similar in many respects to conventional resistance welds, with the exception that no molten metal is formed during the joining process. Titanium has been welded using both variations of resistance welding; i.e., either the conventional technique involving melting or the diffusion-bonding technique. Even conventional spot welds in titanium contain an area around the molten nugget which is diffusion bonded. The bond in this area is generally strong enough to make a significant contribution to the load-carrying ability of the spot weld. However, diffusion-bonded spot welds alone do not meet the requirements of military specifications for resistance welds, and there is a need for future research and development in this area with a view to producing specification coverage.

All resistance-welding processes share some common characteristics. These are discussed in the following section. Subsequent sections discuss each process individually.

4-2.0.1 Cleaning

Careful preweld cleaning is essential to successful resistance welding of titanium alloys. The procedures for cleaning discussed in Paragraph 4-0.2.5 will provide titanium surfaces that meet the requirements for resistance welding. Poor cleaning can result in contamination of the welds being produced with interstitial elements. Poor or variable cleaning can have another bad effect in resistance welding. Much of the initial heat generated during the early stages of resistance welding is localized at the joint interface. This happens because the resistance of the interface to the flow of current is generally higher than the resistance of the bulk material. Thus, the surface resistance of the mating surfaces is an important factor controlling the heat generated during the weld cycle, and it is important that this resistance not fluctuate widely. The surface resistance of any metal is controlled largely by the surface preparation or cleaning techniques that are used prior to welding.

4-2.0.2 Joint Design

Resistance welding always involves joints that consist of overlapping layers of material. Multiple layers may be included in a single joint. In resistance welding, such factors as edge distances and interspot spacings are an important consideration in the selection of a suitable joint design. Another important factor is the initial sheet fit-up, which must not be so great that unusually high forces are required to bring the surfaces into contact.

Many of the joint designs used for resistance welding are not intended to transmit transverse tensile loads. Joints of this type are sometimes referred to as scab or attachment joints.

All joints designed for resistance welding must normally be accessible from both sides the parts being joined. Sufficient clearance must be maintained to allow for the extension of the electrodes and electrode holders in to properly contact the sheets.

4-2.0.3 Material

The titanium-base metals used in resistance welding must be of proven quality and should meet all standards for composition, grade, and heat treatment. Base-metal surface-layer contamination must be avoided prior to resistance welding, or suitable processing steps must be added to remove any contaminated layers. Surfaces to be welded should be flat and smooth. Surface finishes obtained on machined parts or good-quality rolled sheet or plate are adequate.

4-2.0.4 Tooling

The tooling used in resistance welding of titanium is generally similar to the tooling used in welding other materials. Resistance-welding tooling consists of suitable fixtures or jigs to hold

the parts in proper position for welding. Sometimes, tooling is also designed to index the part through the welding equipment to insure that welds are made at the proper positions. The same general rules followed in designing any resistance-welding tooling should be followed for tooling designed for use with titanium. Generally, this means that nonmetallic components should be used exclusively.

4-2.0.5 Process Parameters

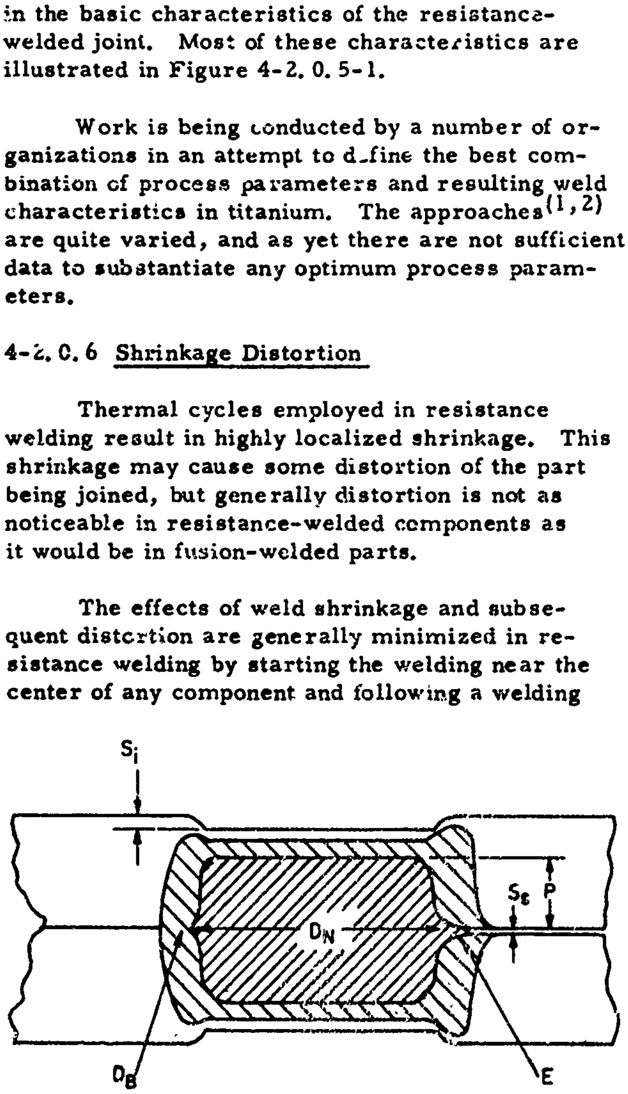
The most important variable process parameters in resistance welding are applied force, welding current, and welding time. In seam welding, the welding speed is also very important. Changes in these parameters will cause changes in the basic characteristics of the resistance-welded joint. Most of these characteristics are illustrated in Figure 4-2.0.5-1.

Work is being conducted by a number of organizations in an attempt to define the best combination of process parameters and resulting weld characteristics in titanium. The approaches[1,2] are quite varied, and as yet there are not sufficient data to substantiate any optimum process parameters.

4-2.0.6 Shrinkage Distortion

Thermal cycles employed in resistance welding result in highly localized shrinkage. This shrinkage may cause some distortion of the part being joined, but generally distortion is not as noticeable in resistance-welded components as it would be in fusion-welded parts.

The effects of weld shrinkage and subsequent distortion are generally minimized in resistance welding by starting the welding near the center of any component and following a welding



DN, weld-nugget diameter
DB, diffusion-bonded zone (heat-affected zone)
E, extrusion
P, penetration
Si, surface indentation
St, sheet separation

FIGURE 4-2.0.5-1. RESISTANCE-WELD FEATURES

sequence that involves moving progressively toward the edges of the component. Sequences of this type are not readily used during seam welding or roll-spot welding, and consequently, distortion may be more of a problem when these processes are used. Selection of improper welding sequences can also introduce various problems with sheet fit-up prior to welding. For example, if three welds are being made in a row and the two outside welds are made first, then there is a good chance that the center weld will be made under conditions where poor sheet fit-up is likely. In a case such as this, the center weld should be made first.

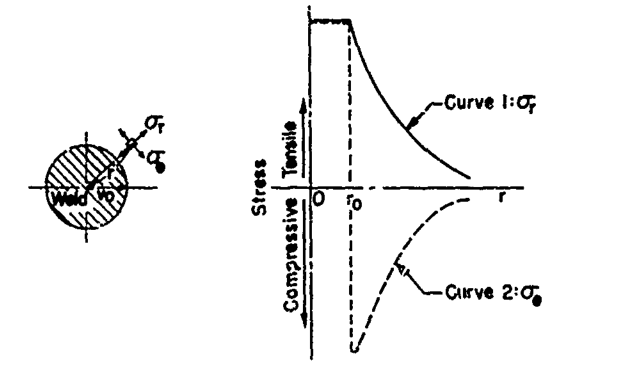
4-2.0.7 Residual Stress

The shrinkage associated with resistance welding always leaves residual stresses in the joint. Very limited published information is available on residual-stress distribution in resistance-welded joints of titanium alloys.[1]

The residual-stress distribution in resistance-welded joints is very dependent on the joint pattern or weld pattern used. The simplest case to consider is the residual stress due to a single spot weld. Figure 4-2.0.7-1 is a schematic representation of the distribution of residual stresses in the area near a single spot weld. The components of stress that are of most concern are those in the radial direction and those in the circumferential direction. The relation between the distance from the weld center and the radial-residual stress is shown by Curve 1 in the figure. Tensile stresses as high as the yield strength of the material may exist in the weld zone. Outside the actual weld zone the tensile residual stress decreases as the distance from the weld area is increased. Curve 2 shows the distribution of the circumferential stress. Again, very high tensile stresses exist within the weld zone; however, outside the weld these stresses are compressive and again fall off as the distance from the weld is increased. From Curve 2 it is apparent that there is an extremely sharp stress gradient around the circumference of any spot weld where the stresses undergo a complete reversal from very high tensile values to high compressive values.

The actual stress distributions in a spot weld in an area very close to the weld are not nearly as simple as shown in Figure 4-2.0.7-1. Very concentrated stresses often exist in the heat-affected zone close to the original interface of the sheets.

When several spot welds are considered instead of just a single spot, the resulting residual-stress patterns are even more complex. An approximate distribution of the residual-stress pattern produced by a series of spot welds can be obtained by the superposition of the residual-stress distributions produced by each weld, as shown in the figure. The interaction between the residual stresses accompanying each individual weld becomes significant when the distance between the welds is short -- probably at any distance less than four times the diameter of the weld.



a. Stress Components b. Relationship Between Radius from the Weld Center, r, and Stresses

FIGURE 4-2.0.7-1. SCHEMATIC REPRESENTATION OF RESIDUAL-STRESS DISTRIBUTION NEAR A SPOT WELD

The residual stresses left in resistance welds can be altered by changes in the welding schedule. Changes in heat input, heat pattern, or possible forging action that may be applied through the electrodes are effective. Some information on the effect of such changes in welding parameters on residual stresses has been obtained, but there are many conflicting aspects to this data.

4-2.0.8 Stress Relief

Residual stresses in resistance welds can be altered and to some extent eliminated by either mechanical or thermal stress-relieving treatments. The application of mechanical stress-relieving methods to spot welds is difficult because of the complexity of the residual stress patterns and the limitations generally imposed by joint configurations. At best, mechanical techniques can probably only result in a redistribution of the residual-stress pattern and not the complete elimination of residual stress. On the other hand, thermal-stress relieving can be used effectively to eliminate all residual stresses resulting from resistance welding. It is difficult to see how such treatments can be employed effectively, though, unless the treatments are conducted in vacuum furnaces. The major problem with methods of thermal-stress relief is that it would be almost impossible to prevent some contamination of the surfaces of titanium components in the overlap area characteristic of resistance-welded structures. Cleaning after such a thermal stress-relief treatment would impose equally severe problems.

As mentioned in the preceding section, perhaps the most fruitful method of controlling residual stresses in resistance-welded joints will be by the selection of suitable process parameters.

4-2.0.9 Inspection

Resistance-welded components are inspected to ensure that the components retain the desired dimensional tolerances and that the welds are of satisfactory quality. In addition to the usual checks on dimensional tolerances, the amount of surface indentation resulting from resistance welding is often measured. Inspection of resistance welds to ensure adequate quality is difficult. Dye-penetrant and X-ray techniques appear to be the only suitable nondestructive inspection methods. However, the latter is subject to limitations in its usefulness. Because of the difficulties associated with inspecting resistance welds, the economic necessity of not allowing a large number of defective welds to get through processing, and the difficulty of repairing defective resistance welds, considerable emphasis is being placed on supplementing or supplanting postweld inspection procedures with in-process controls. Such controls are discussed in Section 4-2.0.11.

4-2.0.10 Specifications

The materials and processes that will be used in titanium-resistance welding are covered by specifications. The basic specifications, as in the case of fusion welding, are generally MIL standards or other applicable Federal Government specifications.(3) Individual aerospace company specifications also are widely used to cover resistance-welding processes.(4)

Almost all resistance-welding specifications require certification of the welding machine that will be used and establishment of a suitable welding schedule prior to the actual start of welding operations. Most specifications then require that various types of test coupons be welded prior to, during, and after any production welding run. Such procedures, while not foolproof, are the best available for use with existing types of equipment and process control.

Applicable military specifications(3) allow the welding of any titanium alloy that has satisfactorily passed tests designed to establish that resistance welding does not harden the weld zone or reduce weld ductility. The requirements state that the direct tension strength of a spot weld must not be less than 25 percent of the minimum shear strength required when tested in an as-welded condition. It is also required that any spot welds subjected to subsequent thermal exposure shall exhibit a similar minimum tension strength after such thermal exposure.

4-2.0.11 Process Monitoring

Recent developments that have been made in the field of monitoring resistance-welding operations are expected to be a major factor in insuring

good weld quality in titanium weldments. The need for such monitoring equipment has long been recognized, and the lack of such equipment in the past has probably prevented more widespread use of resistance welding on aircraft primary structural components. Development of a workable process-monitoring system has proven to be an extremely difficult, although not unexpectedly so, task. Several of the early monitor systems that appeared to be quite promising have failed to live up to expectations. However, the outlook in the immediate future is promising. Most of the current development effort is going into monitoring systems that use the thermal-expansion changes that occur during the creation of a resistance weld. It is interesting to note that development of monitoring equipment based on this principle is being conducted in the United States, England, and the Soviet Union. One investigator[5] has suggested that the thermal-expansion approach might be used in three possible ways: first, as a weld-quality monitor to give a visual or audible indication of weld quality; second, as a open-loop-control system that would correct a weld according to the assessment of the quality of the preceding weld; and finally, as a closed-loop control utilizing the initial expansion characteristics at the early stages in the formation of a weld to feed back a correction if such a correction were deemed necessary from the early signal indications.

While refined process-monitoring equipment is only on the verge of production usefulness,[1] other types of process-monitoring equipment have been used in the resistance-welding field for some time. The necessary equipment and techniques for instrumenting resistance-welding equipment to follow the electrical and force outputs of the equipment are well established. These more established techniques may provide a suitable interim method of process monitoring if the development of more refined equipment is delayed.

4-2.0.12 Defects

Characteristics described as defects in resistance welds are difficult to assess. Defects in resistance welds are generally subdivided into external and internal defects. With the exception of cracks that are exposed to the exterior of the sheets and which are obviously undesirable, the remaining external defects are probably considered as such because they indicate that the welding conditions may not have been exactly right. External defects in this category are sheet separation, pits, metal expulsion, tip pickup, and excessive indentation. With respect to the internal defects of porosity, cracks, and incorrect penetration, there appears to be few guiding test data for their evaluation. However the tolerable level of these defects is outlined in the military specification MIL-W-6858B, which has been reasonably proven in service.

4-2.0.13 Repairs

Very little information is available concerning techniques for the repair of defective spot welds. A number of the defects classified as external defects can be repaired by very light machining of the external weld surfaces. The repair of cracked resistance welds must be accomplished by either a fusion-welding process or through use of a mechanical fastener.

4-2.1 SPOT WELDING

Resistance spot welding has been used more than any other resistance-welding process for joining titanium and its alloys. Spot welding has been used to join titanium in thicknesses ranging from a little under 0.01 inch up to thicknesses totalling 2-1/2 inches. The thickness that can be welded in any given application is limited by the power and force capacity of the available equipment.

In resistance spot welding, all of the heat required to accomplish joining is supplied by the passage of an electric current between two opposed electrode tips that contact the surfaces of the parts to be joined. The electrode tips are held against the workpieces with considerable force so that good electrical contact is maintained throughout the assembly. The configuration involved in spot welding and the relatively short time periods used with the process tend to preclude any contamination from the atmosphere. As a result, there appears to be no need to consider any auxiliary shielding of titanium during resistance spot welding.

In most respects, titanium is an extremely easy material to resistance spot weld. For example, it is much easier to obtain a consistent surface resistance with titanium than it is for many aluminum alloys. The only apparent difficulty with the actual making of titanium resistance spot welds is a problem with metal extrusion between the faying surfaces of the overlapping sheets. Extrusion was illustrated previously in Figure 4-2.0.5-1. With thinner gages of material, extrusion does appear to be a significant problem. However, as the gage thickness is increased, there appears to be a much greater tendency for extrusion to occur. This observation may well be related to the available force capacities on equipment that has been used to resistance weld titanium to date. Several special welding techniques have been developed to minimize the tendency for titanium towards extrusion.[1,6] It is expected that this tendency can be controlled in the future by the adoption of one or more of these techniques.

4-2.1.0 Equipment

Titanium has been successfully welded on almost all types of available conventional resistance-spot-welding equipment. No significant changes in

welding characteristics or static weld properties have been reported that can be attributed to the use of any specific type of welding equipment. However, it is possible that future developments may show such a preference when weld properties are evaluated more thoroughly on the basis of properties such as fatigue or the reduction in residual welding stresses.

4-2.1.1 Welding Conditions

Resistance-spot-welding conditions are primarily controlled by the total thickness of the assembly being welded. Similar welding conditions may be perfectly suitable for making welds in the same total thickness where the number of layers differs significantly. However, for any given thickness or total pileup, various combinations of welding current, time, and applied force may produce similar welds. Other variables such as electrode size and shape are important in controlling such characteristics as metal extrusion, sheet indentation, and sheet separation. The use of slope controls such as preheat, postheat, and additional weld forging cycles were not found necessary in the early welding of titanium alloys. However, the inclusion of some of these special sequences may be a useful means of improving fatigue strength and minimizing the residual stresses in spot-welded joints.

Table 4-2.1.1-1 illustrates some typical spot-welding conditions that have been used on various types of titanium alloys.

4-2.1.2 Properties

Many joint tests of resistance spot welds have been conducted on titanium alloys. Sources of these data are listed in Table 4-2.1.2-1.

The properties measured by tension-shear tests are excellent. Cross-tension values also are good. Cross-tension/tension-shear ratios are low (0.2 to 0.3) but this is to be expected in titanium alloys. The fatigue properties of spot welds are low, but this behavior is characteristic more of the joint type than of titanium alloys. Spot-weld thermal-stability studies indicate some loss in room-temperature properties from exposure at 650, 1000, and 1200 F. Similar exposure at 800 F did not lower the room-temperature properties. A reason for this apparent inconsistency is not apparent. Fracture-toughness tests of spot weldments exhibit properties inferior to comparable TIG fusion weldments.

Spot welding has been used in a number of structural test components. Such tests provide the best evidence of expected weldment performance. Data from such tests has not been available for review.

4-2.2 ROLL-SPOT WELDING

Roll-spot welding is very similar in most respects to standard spot welding. The major difference between the two processes is that in roll-spot welding, wheel-shaped electrodes are used instead of the cylindrical type of electrode used in conventional spot welding. The use of wheel electrodes in roll-spot welding provides a convenient means of indexing the parts between each individual spot weld. Rotation of the wheels is intermittent, with the wheel electrodes being in a fixed position during the actual welding cycle. Electrode wear is more uniformly distributed with a wheel-type electrode than it is with a conventional cylindrical electrode; thus it is possible to make many more welds without dressing of the electrodes when using roll-spot welding. Conversely, there is somewhat less flexibility with roll-spot welding techniques than is available in conventional spot welding.

Equipment for roll-spot welding differs from conventional spot-welding equipment primarily in that provision must be made to accommodate the wheel-shaped electrodes. Also, a suitable drive and indexing mechanism must be provided.

No welding conditions for roll-spot welding of titanium have been found in the literature. It would be expected that these conditions would be very similar to conventional spot-welding conditions.

4-2.3 SEAM WELDING

Seam welding also is similar to spot and roll-spot welding. Seam welds are defined as being a series of overlapping spot welds, and as a result can be made with conventional spot-welding techniques. However, it is considered much better practice to use equipment similar to that described under roll spot welding, in which wheel electrodes replace the conventional cylindrical electrodes. In seam welding, the wheels usually are kept continually in motion. Individual spots are created by timing of the various electrical functions of the welding machine.

The principal advantage of seam welding is that it can be used to produce leak-tight joints. The principal disadvantage is that there is much more distortion with seam welding than with other types of resistance welding.

Very limited data on the properties of seam-welded joints are available.[8,18,26] These data include room-temperature static tensile, and fracture toughness at temperatures of -110, 75, 400, and 650 F for 8Al-1Mo-1V and 6Al-4V alloys. Static tensile properties were comparable in efficiency to the parent metal; however, the fracture toughness was somewhat lower.

TABLE 4-2.1.1-1. RESISTANCE-SPOT-WELDING CONDITIONS

Base Material		Electrode			Machine		Weld Heat		Weld Current		Nugget	
Type	Thickness, inch	Diameter, inch	Radius, inch	Force, lb	Type	Kva	Cycles	Impulses	Ampere	Phase Shift	Diameter, inch	Reference
6Al-4V	0.02	0.5	10	1200	--	--	5	--	--	--	0.150	11
	0.02	0.375	3	795	1Q	75	7	2	--	60%	0.2	8
	0.032	0.375	3	720	3Q	75	2	2	--	55%	0.150	8
	0.035	0.625	3	600	1Q	30	7	--	5,500	--	0.225	10
	0.04	0.375	3	695	1Q	75	4	2	--	10%	0.17	8
	0.05	0.625	6	1100	3Q	150	4	2	--	63%	0.220	7
	0.062	0.625	3	1500	1Q	600	10	--	10,600	--	0.359	10
	0.063	0.50	10	1500	--	--	12	--	--	--	0.350	11
	0.07	0.625	3	1700	1Q	600	12	--	11,500	--	0.391	10
	0.09	0.625	10	1100	3Q	150	4	4	--	35%	0.305	7
	0.093	0.625	3	2400	1Q	600	16	--	12,500	--	0.431	10
	0.125	0.5	10	2300	--	--	14	--	--	--	0.425	11
8Al-1Mo-1V	0.02	0.375	3	720	3Q	75	3	1	--	59%	0.132	8
	0.022	0.625	4	900	3Q	150	3	--	--	35%	--	7
	0.039	0.625	4	1000	3Q	150	6	--	--	40%	--	7
	0.040	0.375	3	760	1Q	200	2	3	--	35%	0.100	8
	0.040	0.375	3	1070	3Q	75	1	4	--	40%	0.113	8
	0.05	0.625	3	1100	3Q	150	4	4	--	50%	0.235	7
	0.05	0.375	10	600	3Q	75	2	4	--	90%	0.210	8
	0.062	0.625	4	1200	3Q	150	7	--	--	45%	--	9
	0.071	0.375	3	1810	3Q	75	2	4	--	60%	0.250	8
	0.09	0.625	10	1100	3Q	150	3	5	--	35%	0.300	7
A-55	0.04	0.625	3	700	3Q	200	4	--	8,300	60%	0.20	12
6Al-6V-2Sn	0.040	0.625	10	1000	--	100	3	5	--	63%	0.235	13
4Al-3Mo-1V	0.020	12.0(a)	6	450	--	125	5	1	--	49%	0.095	14
	0.020	0.5	3	400	--	150	5	1	--	32%	0.130	14
	0.040	12.0(a)	6	1550	--	125	5	1	--	90%	0.190	14
	0.040	0.5	3	800	--	150	5	2	--	45%	0.190	14
	0.063	12.0(a)	6	2000	--	125	7	1	--	97%	0.245	14
	0.063	0.5	10	1200	--	150	7	3	--	55%	0.300	14
	0.063	0.5	10	1200	--	150	6	2	--	52%	0.220	14
	0.125	12.0(a)	7	4700	--	125	5	3	--	75%	0.305	14
	0.125	0.625	10	4700	--	150	8	3	--	73%	0.350	14

(a) Seam weld.

TABLE 4-2. 1. 2-1. SPOT-WELD-PROPERTY DATA SOURCES

Base Alloy[a]	Thickness[b], inch	Type of Tests and Test Temperatures, F	Reference
B	0. 04 to 0. 180	Tensile shear (RT), penetration, and nugget diameter	7
D	0. 04 to 0. 175	Tensile shear (RT), penetration, and nugget diameter	7
B and D	0. 1	Tensile shear[c], cross tension[c], and fracture toughness (-110, 75, 400, 650); thermal stability, and multispot shear (RT)	8
B and D	0. 180	Tensile shear[c], and cross tension[c] (-110, 75, 400, 650), multispot shear (RT)	8
D	0. 044, 0. 078, 0. 124	Tensile shear, cross tension, and multispot fatigue (RT); tensile shear (200, 400, 600, 800, 1000, and 1200) thermal stability (RT)	9
B	0. 070 to 0. 186	Tensile shear (RT, 600, 800, and 1000); cross tension, thermal stability, and thermal-stress stability	10
B	0. 05, 0. 1	Tensile shear, cross tension, and fatigue (RT)	15
A to B A to C B to C	0. 05	Tensile shear, cross tension, and fatigue (RT)	16
D	0. 04, 0. 08	Tensile shear, cross tension, and thermal stability (RT, 600, 800, 1000)	17
E	0. 128	Fatigue (RT and ET)	18
E	--	Air Frame structures - static and repeated load (RT)	19
A	0. 08	Tensile shear, cross tension, and fatigue (RT)	12
Previous 1960 data summarized			11
C	0. 05, 0. 064 0. 08	Tensile shear (RT, 200, 400, 600, 800, 1000) fatigue (RT)	20
D	0. 04 to 1. 5	Various (RT to 650) including all simple tests plus thermal stability, thermal-stress stability, and structures evaluation	1
B, C, D	0. 100	Tensile shear (RT to 650F)	21
D	--	Fatigue (RT)	21
B	0. 120	Tensile shear, impact tension (RT)	22
B	0. 125	Tensile shear, impact tension (RT)	22
B	0. 090	Fatigue (RT)	22
B	0. 080	Tensile shear, impact tension (RT) - use of interfoils	22
B	0. 250	Tensile shear, impact tension (RT) - use of interfoils	22
D	0. 068	Fatigue (RT) - effect of surface treatment	22
B	0. 090	Fatigue (RT) - effect of copper plated interface	22
F	0. 080	Tensile shear (RT and ET)	13
D	0. 090 to 0. 180	Tensile shear (RT and ET)	13
G	0. 080	Tensile shear and cross tension (RT and ET)	23
G	0. 02 to 0. 125	Tensile shear and cross tension (RT)	14
G	0. 02 and 0. 063	Tensile shear and cross section (-100, 75, 500, 800) and thermal stability	14
G	0. 12	Tensile shear and cross tension (RT, 400, 800) and thermal stability (600 to 800)	24
H	0. 080	Tensile shear and cross tension, thermal stability	25

(a) A - cp Ti
B - 6Al-4V
C - 5Al-2. 5Sn
D - 8Al-1Mo-1V
E - 13V-11Cr-3Al
F - 6Al-6V-2Sn
G - 4Al-3Mo-1V
H - 6Al-2Sn-4Zr-2Mo.

(b) Total thickness of test plane.
(c) About one-half of these tests were made after exposure to 1000 F for 10 hours; all others, as welded.

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4-3 Brazing Processes

4-3.0 INTRODUCTION

Brazing has been used for joining titanium experimentally for over 20 years, and in production applications for over 10 years. The widest use of the process with titanium has been in fabricating honeycomb sandwich structures.[1]

A primary problem in brazing titanium sandwich structures is the high rate at which titanium reacts with molten brazing alloys. As a result of these reactions, brittle intermetallic compounds are formed in the joints, and the foil in the core is severely eroded and embrittled.[2]

Another problem is that normal brazing cycles are sometimes incompatible with the heat treatment used for some titanium alloys, such as Ti-6Al-4V. Occasionally, parts made from this alloy have to be solution treated from high temperatures and then aged to develop optimum mechanical properties. However, quenching operations are not practical for sandwich structures. Thus, it appears that the brazing operation for alloys that are to be used in the solution-treated and aged condition should be performed at aging temperatures. Brazing alloys are not now available that flow in the usual aging-temperature range (980 to 1180 F), and additional work to develop them will be required before structures can be brazed in this temperature range.[2]

4-3.0.1 Cleaning

The discussions of titanium cleaning given in Sections 4-0, 4-1, 4-2, 4-4, and 4-5 are generally applicable to cleaning for brazing. Listed below are the steps taken in preparing honeycomb sandwich-structure parts for brazing by one fabricator.[3]

(1) Vapor degrease thoroughly

(2) Soak 10 to 15 minutes in caustic cleaner (180 to 190 F)

(3) Rinse in tap water (120 to 140 F)

(4) Acid clean 15 to 30 seconds (3 percent HF-15 percent HNO_3)

(5) Rinse in tap water (room temperature)

(6) Soak 2 minutes in caustic cleaner (180 to 190 F)

(7) Rinse in tap water (120 to 140 F)

(8) Rinse in distilled or demineralized water (room temperature)

(9) Dry in hot air.

4-3.0.2 Joint Design

Brazing is used with titanium largely for the fabrication of sandwich structures and for the joining of dissimilar metals. The joint designs used used are generally those used for similar applications with other materials.

4-3.0.3 Inspection

Visual, X-ray, and ultrasonic techniques are used for nondestructive inspection of brazed, titanium joints. At one time, 100 percent radiographic inspection was the only accepted determination of braze continuity in sandwich structures. Although radiography remains the primary inspection technique, ultrasonic methods are now becoming more widely used and accepted. Ultrasonic testing is performed with the workpiece submerged in water. The workpiece is scanned by an ultrasonic beam whose returning echos are coupled to an electronic recorder. The method will detect voids as well as light and heavy fillets.[4]

Radiographic examination has now been extended to include X-ray fluoroscopy. This technique does not provide as much definition as an X-ray, but is sufficient to detect gross defects. An image intensifier may be used to attain greater detail.[4]

4-3.0.4 Defects

The defects encountered in brazing titanium are the same as those found in brazing of other materials. Generally, they are in the form of unbounded areas or voids resulting from no filler metal or no flow of the filler. Voids may also result from excessive reaction between the filler metal and the base metal, particularly in silver alloys.

4-3.1 PROCESS APPLICATION

In this section, various factors of the brazing process as they apply to the brazing of titanium are discussed.

4-3.1.1 Filler Metals

To be useful as a brazing filler metal, an alloy must melt within a desired temperature range, it must wet the base material involved, and, while molten, it should flow to some extent on the base metal. Of all the various metals and alloys that meet one or more of these criteria, silver-base alloys have been used with the most success

for the brazing of titanium. Not all of the silver-base alloys are suitable for use with titanium, but several have been found that display many desirable properties. The most useful alloys are silver-lithium, silver-aluminum-manganese, and silver-copper-lithium. The most common problem encountered with other brazing alloys, which on the surface appear usable, is that they react readily with titanium. Only through the use of very short brazing times is it possible to prevent excessive alloying between the filler metal and the titanium-base material.

Brazing alloys for use with titanium alloys must be selected with care, depending on the alloy being joined and its thickness, mass, penetration tolerance, and service requirements. A wide variety of brazing alloys have been investigated, some of which are commercially available.

The silver-lithium alloys are used in a composition ranging from 0.5 to 3.0 percent lithium. However, joints made with these alloys do not have good oxidation resistance in air at temperatures of about 800 F, and the joint strength is seriously degraded by exposure to these conditions. Joints made with the silver-lithium alloys also appear to have poor corrosion resistance in salt-spray environments.

The most promising alloys at present are those containing aluminum and manganese in a silver base. Alloys of this type have been used for a number of years. A typical composition is Ag-5Al-1Mn. Although this and similar alloys appear to be somewhat better than the silver-lithium alloys with respect to oxidation resistance and salt-spray corrosion resistance, there is still some reluctance to use the materials where exposure to these conditions can be expected. The brazing temperature for the silver-aluminum-manganese alloys ranges between about 1450 to 1650 F.

Recent data indicate that all silver-base brazing alloys may degrade the stress-rupture properties of titanium. A similar effect may occur with brazing alloys based on other metals such as gold, platinum, and palladium.

Among other brazing alloys of interest are the silver-cadmium-zinc brazing filler metals that have been developed and used for oxyacetylene torch-brazing applications. Consistent joint tensile strengths ranging from 40,000 to 50,000 psi and single-lap-joint shear-strength values in excess of 30,000 psi are reported. Alloys of this type, containing 30 percent silver, have been developed for joining titanium to itself, steel, stainless steel, and silver alloys.[5] Fluxes for these alloys have also been developed.

Another brazing alloy with very desirable characteristics is an experimental palladium-base alloy.[6] Originally Pd-14.3Ag-4.6Si, it has since been changed to Pd-15.4Ag-3.5Si. It has excellent flow characteristics and a liquidus of 1280 F, i.e., below the beta-transition temperature of pure titanium. This alloy forms a metallurgical bond, with alloy interfacial penetration of 0.0015 inch into titanium. Joint strengths in the range of 74,000 to 89,000 psi have been obtained. Connections brazed with the alloy are inert to nitric acid and, under vacuum, helium leakage is less than 0.63 cm^3/yr.[7]

Four recently developed braze-alloy compositions that show much promise for joining titanium are RM-8 (43.0Ti-43.0Zr-12.0Ni-2.0Be), RM-12 (45.0Ti-45.0Zr-8.0Ni-2.0Be), CS-217 (47.5Ti-47. Zr-5.0Be), and CS-217C (45.12Ti-45.12Zr-4.76Be-5.0Al).[8] These alloys have exhibited improved crevice corrosion resistance over the standard silver braze alloys. They also possess levels of strength, strain-accommodation ability, peel toughness, and oxidation resistance comparable to the best silver brazes. In addition, they flow at temperatures safely below the beta-transus temperatures of the foil alloys.

4-3.1.2 Methods

The methods that have been used to braze titanium are generally similar to those developed for other materials, such as stainless steel. With titanium, however, particular care must be taken to insure against contamination of the base metal during the brazing cycle. This has necessitated the careful use of either inert-gas or vacuum environments during the brazing cycle. Heating for brazing is generally accomplished in retorts placed in furnaces or by some type of radiant heating device such as a quartz lamp panel. Some success has been reported with a conventional oxyacetylene torch-brazing technique, but this method is not considered applicable to airframe components. In general, it can be concluded that the brazing methods used on titanium are very demanding of careful control throughout all steps to ensure that the titanium base material is not contaminated from any source. Specific methods, relating to the two major applications of titanium brazing, are discussed below.

4-3.1.2.1 Honeycomb Sandwich Structures

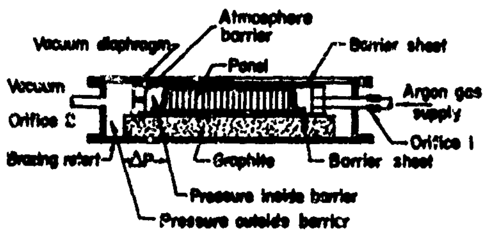
In furnace and retort brazing operations of honeycomb sandwich structures, titanium can be contaminated by leakage of air into the brazing atmosphere. One fabricator has developed a double-layer, inert-gas shroud retort to ensure against such leakage.[3] In addition to providing good protection against contaminants, the process provides for lower argon consumption and shorter brazing cycles than were obtained with more conventional retorts. The technique permits the use of gas or electric furnaces and eliminates the need for a secondary, argon-filled retort around the brazing retort.

With this method, titanium contamination is prevented both dynamically and mechanically. Protection is afforded by two separate atmosphere zones and a pressure differential that ensures more effective protection. The system, as shown in Figure 4-3.1.2.1-1, is larger tham most retorts and is divided into two pressure zones. The outer zone is maintained at a reduced pressure, while the inner zone is filled with argon gas. Air entering through a leak in the retort is removed between the retort and the barrier and exhausted through the vacuum tube. The pressure differential helps hold the parts in intimate contact during the brazing cycle.

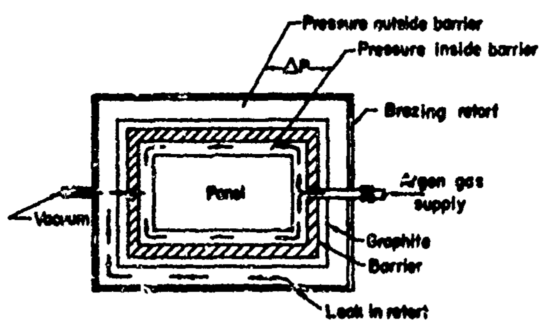
4-3.1.2.2 Dissimilar Metals

Brazed tube joints of titanium to 320 stainless steel have been evaluated.[9] These were sleeve joints brazed by induction heating in argon using a 98 percent silver-2 percent lithium alloy. The process was successful, but the joints showed poor corrosion resistance in salt-spray tests. Failures occurred within 100 hours. No benefits were derived from either silver plating the titanium or nickel plating the stainless steel.

More recent work by this same source was concerned with the usefulness of Dynabraze filler metals for brazing titanium core-17-7PH stainless steel-skin sandwich structures. Panels brazed with Dynabraze B (95.0Ag-5Al-0.5-1.0Mn) showed a 50-hour salt-spray life and withstood 100 hours' exposure at 800 F. Dynabraze C deteriorated in the salt-spray test. Node flow and the fillet size and shape were not good with these alloys.[10]



a. Honeycomb Panel Shielded by Two Pressure Zones to Keep Contaminants Out



b. When Retort Leaks, Contaminants Are Exhausted Through Evacuation Tube

FIGURE 4-3.1.2.1-1. DOUBLE-WALL RETORT SYSTEM FOR BRAZING TITANIUM-ALLOYS SANDWICH PANELS[3]

A transition joint between titanium (Ti-6Al-4V) and stainless steel (304L) tubing was used in the Gemini spacecraft.[11] This joint was vacuum-induction brazed using an 82 percent gold-18 percent nickel brazing alloy. The existence of a brittle intermetallic layer and indications of cracks revealed by dye-penetrant tests lead to extended joint evaluations. Attempts to induce a crack by applying a two-point bending load were not successful. Cracks were induced by continued bending. The only failure occurred by fatigue outside the joint area. It was concluded that the brazed joint would sustain loads in excess of the yield strength of the stainless steel and remain leak-free. The success of this joint has been attributed to strict control of all the variables of the brazing procedure.[12] These included very rapid induction heating, critical joint gap control, and control of the time (within seconds) the molten gold-nickel alloy was in contact with the titanium. The developers of this technique have also reported on the use of precisely controlled brazing procedures and properly chosen silver-base alloys to produce titanium-mild steel and titanium-Vascojet 1000 joints.

The experimental palladium alloy discussed in Section 4-3.1.1 is also useful in making titanium-to-stainless steel joints.

4-3.1.3 Properties

An important factor in selecting braze filler metals is the effect that the required thermal cycle will have on base-metal properties. With titanium, this factor is important primarily when brazing a heat-treatable alloy.

Several programs have been conducted to develop braze filler metals for titanium that are compatible with desired heat-treating cycles of titanium alloys. In general, these programs have not been successful in identifying brazing alloys that provide the necessary combination of properties to be useful. This fact limits the usefulness of brazing in the joining of titanium alloys where heat treatment is used to obtain desirable strength properties.

Table 4-3.1.3-1 shows tensile properties for copper diffusion-brazed joints in Ti-6Al-4V alloy. Although these joints were diffusion brazed, a liquid phase was involved, and it is felt these properties are significant and representative of potential strengths in brazed titanium joints.

As stated above, the effect of the brazing cycle on base-metal properties is an important factor in selecting brazing filler metals for titanium alloys. Several general rules apply to this selection.[1]

Ideally, the brazing temperature should be 100 to 150 F below the beta transus for the alloy. In the alpha-beta alloys, base-metal ductility may

TABLE 4-3.1.3-1. TENSILE PROPERTIES OF COPPER DIFFUSION BRAZED JOINTS, Ti-6Al-4V(13)

Exposure	None		600		600	
Exposure Time, hr:	None		500		1000	
Environment:	None		NaCl(a)		NaCl(a)	
	F_{tu}, ksi	F_{ty}, ksi	F_{tu}, ksi	F_{ty}, ksi	F_{tu}, ksi	F_{ty}, ksi
Copper Diffusion Braze (1900 F for 60 min)	139	121	145	126	149	128
Ti-6Al-4V Base Metal (1900 F for 60 min)	137	117	145	126	147	127

(a) Aqueous NaCl slurry was applied to the specimens.

be impaired if the brazing temperature exceeds the beta transus. The beta transus may be exceeded in brazing beta-type alloys without impairing base-metal properties, but if the temperature is too high the ductility of the alloy after heat treatment may be impaired.

The brazing temperature may affect the ultimate and yield strengths of heat-treatable alloys after final heat treatment unless it is possible to fully heat treat the assembly after brazing. For example, full heat treatments for most of the heat-treatable alpha-beta alloys consist of two operations: (1) solution treatments to adjust the ratio of alpha and beta phases for optimum heat-treatment response and (2) age-hardening treatments. If the brazing operation is part of the heat-treatment cycle, it is desirable to braze at either the solution-treating or age-hardening temperatures. However, the age-hardening temperatures are low (800 to 1100 F) and satisfactory brazing alloys that melt and flow at these temperatures are not available.

If the brazing operation is performed near the solution-treating temperature as part of the heat-treating operation, then the cooling rate from brazing temperatures may affect the final properties of the base metals. This is especially true for alloys such as Ti-6Al-4V, which have low beta content and require rapid cooling from solution-treating temperature to obtain good heat-treatment response.

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4-4 Adhesive Bonding

4-4.0 INTRODUCTION

Although adhesive-bonded joints have been used extensively in the fabrication of aircraft, their use with titanium structures is still quite limited. The British pioneered in the of synthetic adhesives for primary structural joints in aircraft during World War II. Experience was first gained with wooden aircraft. It was later extended to wood-to-metal and metal-to-metal joints in numerous European and American military and commercial aircraft.[1,2] However, aluminum has been used in all of the reported European applications and in the bulk of work done in this country. Although titanium has been used extensively in recent aircraft, riveted, rather than adhesive-bonded, construction has been used. Nonetheless, much of the adhesive bonding work that has been done in aircraft structures can be applied to titanium bonding.

The discussion in this handbook will relate to organic adhesives only. Much work was done with inorganic adhesives in the late 1950s, but although they offer high mechanical strengths, a problem of brittleness was never resolved satisfactorily. Apparently, there is presently no production application of inorganic adhesives in titanium bonding.

4-4.0.1 Advantages of Adhesive Bonding

As indicated above, most of the adhesive-bonding technology has been developed for aluminum and steels. However, the techniques are generally applicable to titanium as well. Although knowledge about adhesive bonding is not yet as widespread throughout industry as knowledge of such other joining techniques as riveting, welding, and brazing, it is known to offer certain advantages.[1] These include:

(1) Mechanical strength. Properly designed and constructed adhesive-bonded joints have shown room-temperature lap-shear tensile strengths ranging up to 7000 psi. In some cases, adhesion has been so strong that fracture has been accompanied by pulling pieces of metal from the surface at the bond plane. Because the load is distributed more evenly across the joint than with rivets or spot welds, adhesive-bonded joints are often superior under cyclic loading conditions.

(2) Mechanical damping. Organic adhesives have a high damping capacity, which reduces the sensitivity to vibrational loading and helps to lower the noise level.

(3) Smooth external appearance. Smooth, unbroken lines, which are essential on the exterior of an aircraft, can be obtained with adhesive bonding.

(4) Use in the joining of dissimilar metals. Because of the apparent electrical insulating properties of adhesives, dissimilar metals can be joined with much less chance of galvanic corrosion. This allows greater freedom in choosing materials.

(5) Usability with thin or brittle materials. Mechanical fastening and welding become difficult with materials of 0.040 inch and less, but adhesive-bonded joints are easily made in these thin materials. With brittle materials, adhesive bonding offers freedom from high-intensity or sudden mechanical loading during the bonding operation.

(6) Possible weight and size reduction. Butt-welded joints remain the lightest possible type of construction. Adhesive-bonded joints, however, offer a considerable advantage in weight and size over mechanical fastening for joining of thin or light materials.

(7) Combined sealing and structural function. Certain adhesives, particularly the elastomers and elastomer-phenolic blends, are often used as sealants as well as structural adhesives. An example of this type of use is the "wet wing" type of aircraft, which uses no separate fuel tank. The fuel is contained within the wing by 100 percent sealing of structural joints.

(8) Minimum finishing required. Little or no work is required on an adhesive-bonded joint after curing. In some cases, it may be necessary to remove any adhesive that extends behond the joint, but this is easily accomplished.

(9) No thermal damage to metals. The curing temperatures required for adsives are below the range that will cause any metallurgical change in titanium.

(10) Low cost. When the entire cost of making a joint is completely accounted for, adhesive bonding is often less expensive than other joining methods.

4-4.0.2 Disadvantages of Adhesive Bonding

There are certain limitations to adhesive bonding, including:[1]

(1) Limited service conditions. The upper service-temperature limit that a good epoxy or phenolic adhesive can withstand for an indefinite time is usually given as about 350 F. There are some polyimide-based adhesives available that will withstand 500 F for several thousand hours. hours.[2] It should be noted that recent Russian work has reported tests made at temperatures up to 1832 F.[3]

(2) Residual stresses. Residual stresses arise in an adhesive-bonded joint because of differential thermal expansion between the adhesive and adherend. They become a more serious problem as curing temperatures increase. Generally, the adhesive layer has the higher thermal-expansion coefficient, and is put in tension as the joint cools following curing. These stresses cannot be readily annealed out. The use of a thicker glue line, a more resilient adhesive, or postcuring will minimize them, however.

(3) Need for accurate joint fitup. Clearance between adherends to be adhesively joined should be uniform and usually somewhere between 0.005 and 0.010 inch.

(4) Requirement for a high standard of cleanliness. The adherend surfaces for adhesive-bonded joints must be precleaned and kept clean until bonded. There is no cleaning action inherent to the process as with welding, brazing, and soldering.

(5) Susceptibility to weather, solvent, and moisture attack. Adhesives must be carefully chosen for a particular application, since there is a danger of degradation of an adhesive by its environment. For example, thermoplastic adhesives are subject to attack by solvents, and cyanoacrylates are moisture sensitive.

(6) Requirement for curing time for maximum properties to develop. Curing time for adhesives may range from a few minutes to several hours. The adherends must be fixtured during curing so there is no relative motion between them. The seriousness of this problem may be reduced by such means as designing self-clamping parts or by curing at the same time the paint is baked on.

(7) Possibility that the adhesive may react with the material being joined. Care must be taken in the selection of adhesives, fillers, extenders, and curing agents to avoid compounds that will corrode the adherends.

(8) Possibility that the adhesive may outgas. Any organic material in enclosed or hermetically sealed devices should be used with caution. Sufficient vapor may be given off from the organic material during and after curing to impair the function of the device.

(9) Possibility that adhesive may degrade under radiation. Adhesive bonding is the most radiation sensitive of the joining processes. Work is being done to evaluate this factor in the upper-atmosphere radiation fields, but no results are presently available.

4-4.0.3 Elements of Process

As with all joining processes, adhesive bonding is broken into three major steps -- pretreatment, making the joint, and posttreatment.[1]

During pretreatment, the surfaces to be joined, the adherends, are properly cleaned and conditioned. The conditioning may involve application of an electroplate or a chemical conversion coating, and may be followed by application of a primer adhesive in a volatile solvent. Following this conditioning, the adhesive is placed on the area to be bonded.

The joint is made by placing both adherends in contact with the adhesive in their desired relative position. Some means is provided to hold them in this position. Time is allowed for the adhesive to cure, or harden, during which period many adhesives require the application of external heating. After the cure, the adhesive is a solid and, if the joint is proper, is distributed evenly between the adherends in a line several thousandths of an inch thick.

Posttreatment may include a second curing cycle, or postcure. It may also include the removal of any excess adhesive that has oozed out of the bond area. For critical joints, the posttreatment inspection may include nondestructive testing.

4-4.0.4 Surface Cleaning and Preparation

Perhaps the most critical step in achieving a good adhesive bond is the preparation of the surfaces to be joined. Figure 4-4.0.4-1 shows the sequence of operations common to most adherend-preparation processes. Numerous procedures for preparation of titanium alloys are reported in the literature, but they differ mainly only in the compositions of the etching and surface-conditioning reagents.

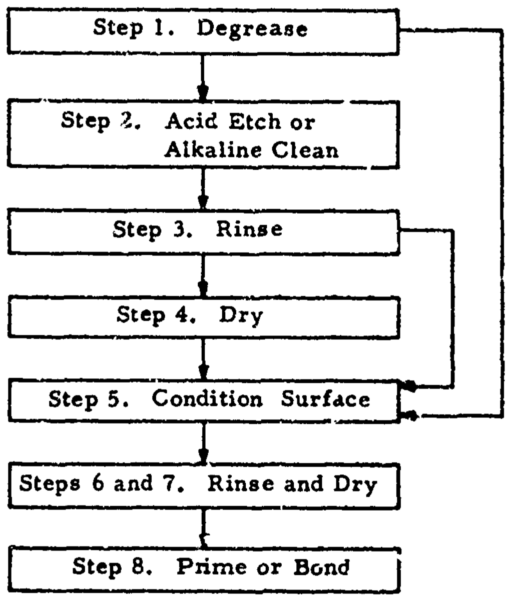


FIGURE 4-4.0.4-1. FLOW CHART OF SURFACE-PREPARATION PROCESSES FOR ADHESIVE BONDING OF TITANIUM ALLOYS[1]

Degreasing and acid etching or alkaline cleaning operations have already been discussed in Section 4-0.2.5 of this report, and reference should be made to that section. It is important to repeat, however, that chlorinated solvents, if incompletely removed from titanium alloys, can give rise to stress-corrosion cracking in the vicinity of subsequently made welds. Since welding of titanium is often done in the same plant as adhesive bonding and is sometimes done on the same parts, best practice is to avoid the use of chlorinates solvents completely. Several airframe manufacturers who fabricate titanium alloys no longer permit use of chlorinated solvents. [1]

Abrasive blasting may also be used to remove the oxide layer. Additional, specific information is offered in the following discussion.

Wiping of parts may be necessary where they are too large for treatment tanks. In this case, badly contaminated points on the surface should be pretreated by scrubbing or mechanical abrasion. When abrasion is used, care must be taken to remove the abrasive residue.

Treatment in strong acidic etching solutions, particularly sulfuric acid, can result in appreciable hydrogen pickup. This can result in embrittlement and may also cause porosity in titanium alloy welds. [4] Hydrogen pickup can be minimized by using a pickling solution containing ten parts of nitric acid to one part of hydrofluoric acid by volume. [5]

Since residual etching or cleaning solutions may cause corrosion of the joint, thorough rinsing is necessary to completely remove these solutions. Opinions differ as to whether water rinses should be hot or cold; tap, demineralized, or distilled; immersion or spray, or whether the hot rinse should precede the cold. Tap water is not generally recommended, however, as it may reintroduce various impurities, including chlorine.

If drying is necessary after the rinse, it can be done in air as clean, still, and dust-free as possible, or it can be forced by a clean, warm-air blast. If forced drying is used with titanium alloys, the temperature should be limited in order to slow oxide-film growth. [1]

The conditioning step of surface preparation involves forming a corrosion-preventing film or seal on the adherend surface. This film is controlled as to chemical composition and thickness. The composition of the film may be the most important single factor controlling the strength of the adhesive-bonded joint under the desired service conditions. There is no systematic means available for choosing the proper solution for a given application, and this must be done by testing. The films typically used for titanium are complex mixtures of phosphates, fluorides, chromates, sulfates, and nitrates. [1]

The surface may be sealed anodically as well as chemically. Anodic solutions contain a chelating agent or an active acid to attack the titanium, and an acidic or alkaline electrolyte to increase conductivity. Anodic coatings are not good barriers against further oxidation, and generally require sealing with a silane primer prior to bonding. [2]

Titanium should be bonded no later than 8 hours after surface preparation; otherwise, surface contamination will negate the preparation process. Preferably, bonding should be performed immediately after preparation. When this is not possible, the prepared surface should be primed according to the adhesive manufacturer's directions. The primed parts should then be stored in a clean, dry place, preferably protected by a cover of some sort, until ready for bonding. Cleaned parts should be handled only with clean cotton or nylon gloves. [1]

The various procedures that have been used to prepare titanium-alloy surfaces for adhesive bonding are summarized in Reference (1). Convair, Ft. Worth, studied 31 procedures for preparing titanium and selected the following phosphate-fluoride method as best, at least for high-temperature application:[4]

(1) Wipe with methyl ethyl ketone

(2) Degrease with trichloroethylene vapor*

*See comments above regarding precautions on the use of chlorinated solvents.

(3) Pickle in the following water solution at room temperature for 30 seconds:

Nitric acid (15 percent by volume of 70 percent HNO_3 solution)

Hydrofluoric acid (3 percent by volume of 50 percent HF solution)

(4) Rinse in tap water at room temperature

(5) Immerse in the following water solution at room temperature for 2 minutes:

Trisodium phosphate: 50 grams/liter of solution

Potassium fluoride: 20 grams/liter of solution

Hydrofluoric acid (50 percent solution): 26 milliliters/liter of solution

(6) Rinse in tap water at room temperature

(7) Soak in 150 F tap water for 15 minutes

(8) Spray with distilled water and air dry.

4-4.0.5 Residual Stresses

Thermal-expansion coefficients of adhesives as a class of materials are higher than those of metals. It has already been mentioned that this mismatch can cause residual stresses in the joint with temperature changes. An adhesive bond will tend to be under internal stress on cooling after the cure, the adhesive tending to be in tension. If the adhesive has shrunk during the cure, the tensile stress will be even greater in the completed joint. Because of these residual stresses, delayed room-temperature failure may frequently occur. This can usually be overcome by adjustment of the curing cycle. If the joint is intended for service below room temperature, even greater stresses will develop during cooling, which may result in immediate and spontaneous failure of the bond.

One method sometimes used to reduce the thermal-expansion mismatch is to fill the adhesive with metal powder, preferably of the metal being bonded. This may cause loss of adhesion, however.

A resilient adhesive will adjust to the internal stresses in the joint better than a hard or brittle one. Often, adhesives intended for use with metals are complex mixtures of a base epoxy or phenolic resin blended with an elastomer, such as nitrile rubber, or a thermoplastic. These materials increase the resiliency of the adhesive.

4-4.0.6 Use of Solvent Carriers

The use of solvents in metal-bonding adhesives results in greatly extended cure times and porous bonds. This is because of the inability of the solvents to escape from between nonporous surfaces. For this reason, adhesives used to bond metals contain only small amounts of the solvents and volatile materials that are commonly found in adhesives used to bond porous materials. Primers used with metal joints do contain solvents that should be allowed to evaporate before the bonding operation is performed. Adhesives containing solvents can be used with metals that are coated and left apart until most of the solvent has evaporated.

4-4.0.7 Inspection and Testing

The importance of testing in producing acceptable adhesive-bonded joints cannot be overemphasized. Inspection of adherend-surface preparation and testing and evaluation of adhesives and tooling are as important as testing of the completed joint.

4-4.0.7.1 Surface Preparation

The most commonly used test for surface cleanliness, and the most easily applied, is the water-break test.[1] This can be used at any stage of the cleaning process. The surface is presumed free of harmful organic films if a drop of distilled water wets the metal surface and spreads out, or if a distilled-water film on the surface does not break up into individual droplets. If a surface is uniformly wet by distilled water it will probably also be wet by an adhesive. An organic solvent has sometimes been substituted in this test but is not suitable. The solvent may have the power of dissolving any organic film present and then wetting the surface. The water-break test does not give information concerning the strength of any film present, so it is not a test of attainable adhesive-bond strength.

4-4.0.7.2 Adhesive Evaluation

Constant checks of an adhesive's bonding strength are essential. For critical applications, lot-to-lot variation in adhesives can be significant. Materials already in the plant must be checked before and during use to assure that they have not deteriorated with age or improper storage conditions. There are several means of mechanically testing bond strength.

One of these is the simple overlap tensile shear test. The simple lap joint pulled in tension is easy to make and test and provides meaningful comparative results.[6] Dimensions of the tensile-shear specimen set forth in Federal Test Method No. 175, Tentative Standard Method 1033.1-T, are generally accepted. A sketch of the specimen is shown in Figure 4-4.0.7.2-1.

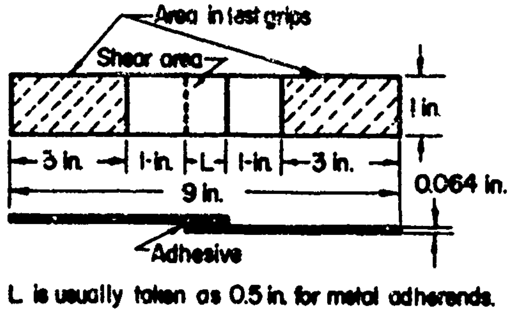


FIGURE 4-4.0.7.2-1. CONFIGURATION OF SIMPLE-LAP TENSILE-SHEAR-TEST SPECIMEN

Another mechanical test that may be used in adhesive evaluation is the tee-peel test. A specimen for this is shown in Figure 4-4.0.7.2-2. The results of this test are given in terms of strain energy per unit width of specimen, in.-lb/in. Thus the adherend thickness can influence the result.

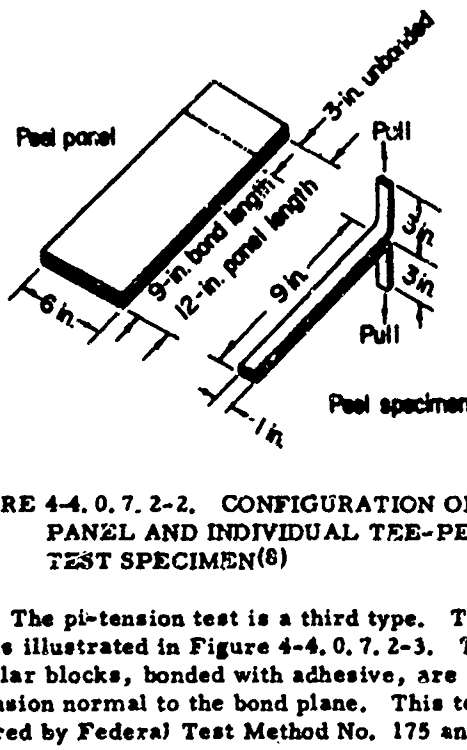


FIGURE 4-4.0.7.2-2. CONFIGURATION OF PANEL AND INDIVIDUAL TEE-PEEL-TEST SPECIMEN[8]

The pi-tension test is a third type. This test is illustrated in Figure 4-4.0.7.2-3. Two circular blocks, bonded with adhesive, are pulled in tension normal to the bond plane. This test is covered by Federal Test Method No. 175 and has been adapted for testing adherence of honeycomb-panel cover sheets to core. It is a specialized test, since results will be influenced by the details of core configuration.

Other mechanical tests are applied to honeycomb. These include the climbing drum-peel test

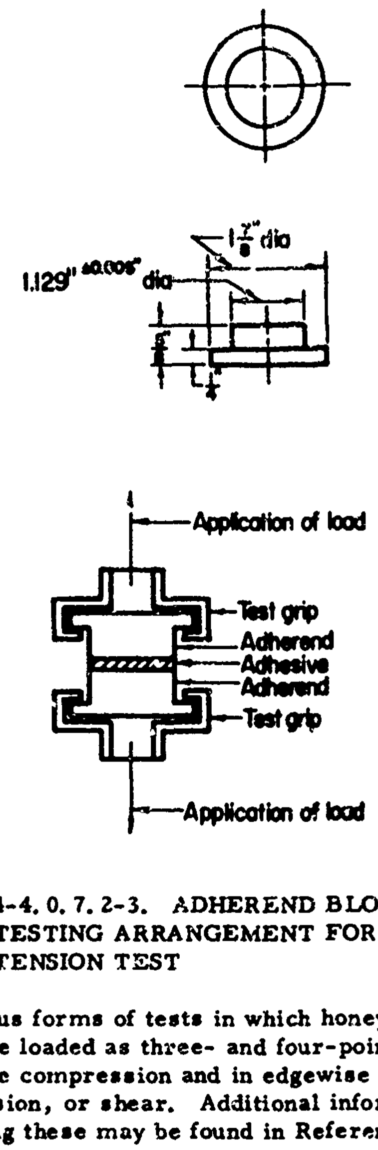


FIGURE 4-4.0.7.2-3. ADHEREND BLOCK AND TESTING ARRANGEMENT FOR PI-TENSION TEST

and various forms of tests in which honeycomb panels are loaded as three- and four-point beams in flatwise compression and in edgewise compression, tension, or shear. Additional information concerning these may be found in References (6) and (7).

4-4.0.7.3 Tooling Evaluation

Before bonding tools and fixtures are placed in production, they must be proven by making destructive tests on parts bonded with them. Process equipment and instrumentation must be periodically checked to insure satisfactory operation. On-the-spot inspection during adhesive bonding is necessary to enable adjustment of processing equipment with a minimum scrap loss of product.

4-4.0.7.4 Destructive Testing

Destructive testing is not desirable because it leaves the bonded parts unsuitable for service. One means of overcoming this limitation is to use small, detachable test coupons for destructive tests. Their use must be planned when tooling is designed. The specific tests performed will depend on the nature of the bonded part and its intended service. Even with the use of coupons, destructive

testing of some of the parts themselves will be necessary.

4-4.0.7.5 Nondestructive Testing

The use of sonic waves is the most widely used nondestructive testing method for adhesive-bonded metal parts. Some X-ray examination has been done, but adhesive bonds are transparent to X-rays of the energies necessary to penetrate metal cores and face sheets. The ultrasonic test methods are adaptations of those developed for metals. They may be conducted with parts immersed in water or with dry parts with only a fluid-coupled transducer. There are several types of sonic test equipment available, including the Stud-Meter, the Coinda-scope, and the Fokker Bond Tester.(1) Correlations have been made between tester reading and tensile-shear strength, so that as-bonded strengths can be predicted.(9) Several aerospace manufacturers have worked out these correlations for their particular bonding systems, and are presently using them in quality control. One unsuccessful attempt has been made to use the sonic tester to detect in-service bond-strength deterioration.(10)

4-4.0.8 Specifications

A complete summary of Government, military, and industry-wide specifications relating to adhesive bonding is available in Reference (11). Supplemental reviews to Reference (11), at 3-month intervals, are available from the source indicated. Other reliable references on specifications are References (12) and (13).

4-4.1 JOINT DESIGN

The best strength properties of adhesives are generally obtained under shear loading. For this reason, lap joints are prefereable wherever they can possibly be used. Although they are difficult to obtain, detailed stress analyses of a adhesive-bonded joints have been made. Part of the difficulty in obtaining such analyses arises from the nonlinear stress-strain characteristics of adhesives. A recent survey report(14) presents a critical review of present knowledge in this area. For this discussion, it is sufficient to point out that stresses are not uniformly distributed across an adhesive joint. As shown in Figure 4-4.1-1, stress concentrations occur at the free edges of the glue line. When the adherends are thin enough to be bent, as shown in this figure, the stress concentrations in the plane of the adhesive are accompanied by the appearance of a tensile stress in the free edges of the adhesive in a direction normal to the glue line, causing a tendency toward peeling.

A wide variety of adhesive-bonded joints are shown in Figures 4-4.1-2 through 4-4.1-14. All of these could be applicable to titanium structures in a supersonic aircraft. Figures 4-4.1-2 and 4-4.1-3 present a compilation of the numerous designs developed for adhesive-bonded lap joints. These figures also present data on adherend rigidity and stress concentrations in the joints. Selection of a particular joint geometry for a given application is a compromise between strength and cost of preparation. Other types of joints can also be designed to place the glue line in shear. Some corner-joint designs are shown in Figure 4-4.1-4. Sheet-metal corner joints usually require a third component, which may be a formed, machined, or extruded part. Tee joints can be variously designed, depending on the type of loading to be encountered. Some edge, angle, and tee-joint designs are shown in Figure 4-4.1-5. Tubular joints in hollow components are shown in Figure 4-4.1-6. These should be designed with sleeves around the bond area, or by sizing one adherend to fit within the other. Where a butt joint is made in thick materials, the edges should be so prepared that a shearing component exists along at least part of the glue line, as shown in Figure 4-4.1-7. Similarly designed faces with radial symmetry can be used when bonding solid rods. Thin strips of metal that are likely to peel in flexure loading can be bonded in several ways, as shown in Figure 4-4.1-8.

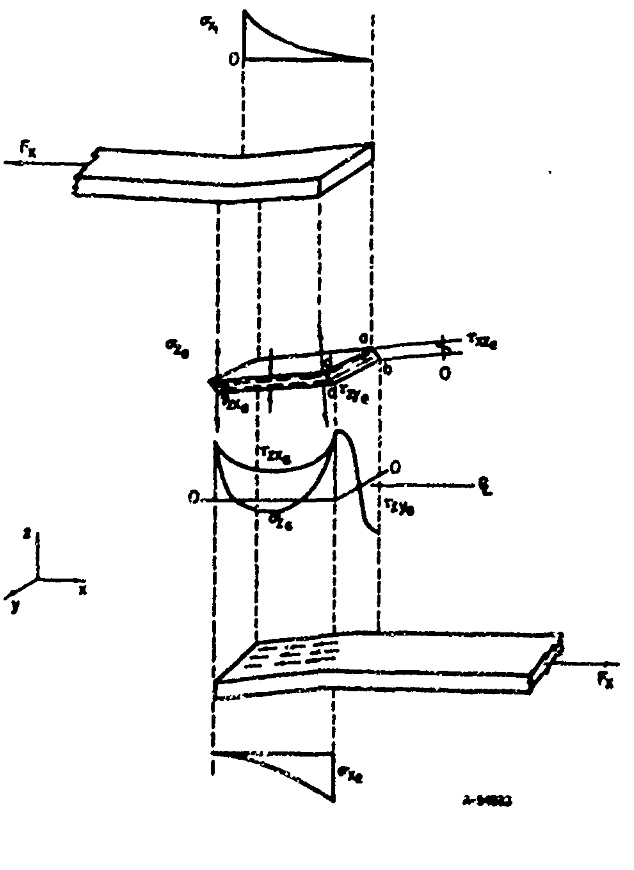
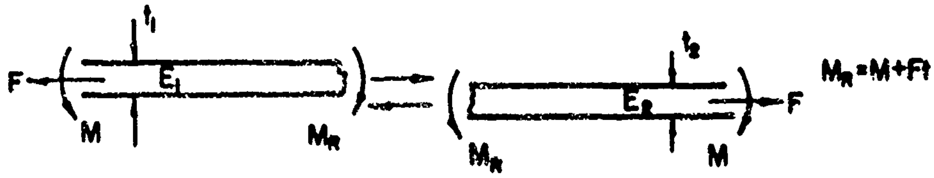
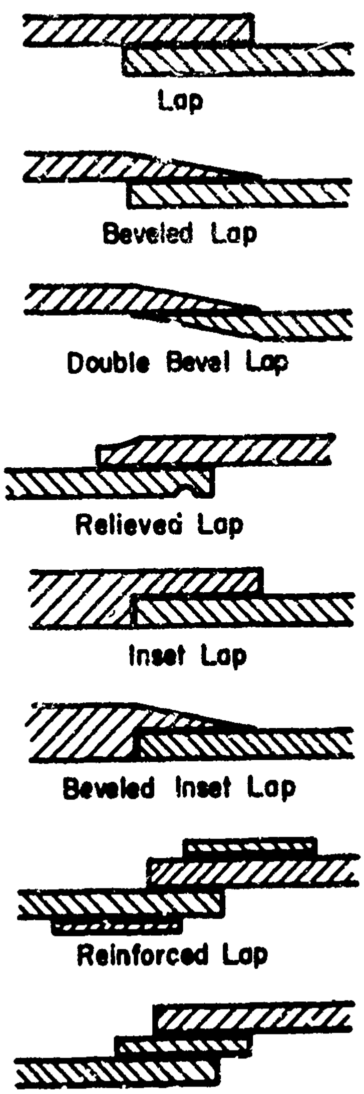


FIGURE 4-4.1-1. VARIATION IN STRESSES IN TENSILE-LOADED SIMPLE LAP JOINT(1)

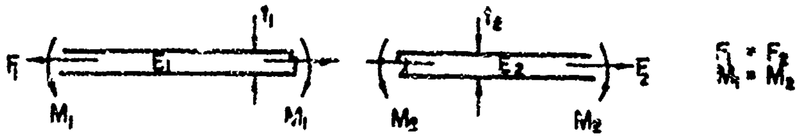


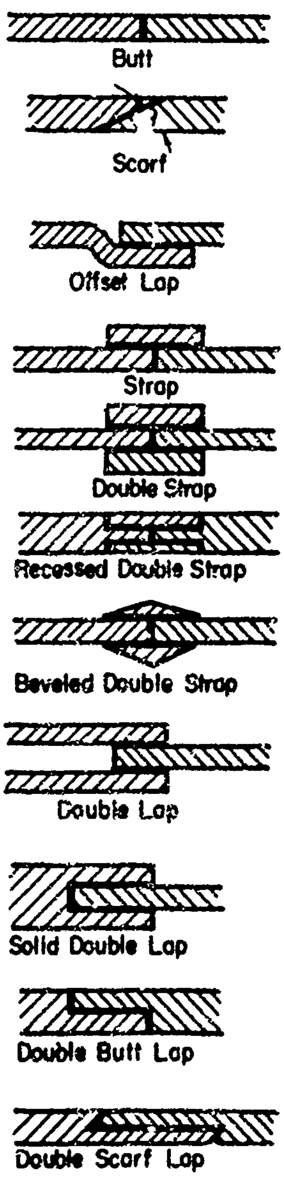


	Rigidity of Adherends	Stress Concentrations Under: F	-F	M
Lap	$E_1 = E_2$	Major	Major	Major
	$E_1 > E$	Major	Major	Major
Beveled Lap	$E_1 = E_2$	Major	Major	Major
	$E_1 > E_2$	Moderate	Moderate	Major
Double Bevel Lap	$E_1 = E_2$	Minor	Minor	Moderate
	$E_1 > E_2$	Moderate	Moderate	Major
Relieved Lap	$E_1 = E_2$	Moderate	Moderate	Moderate
	$E_1 > E_2$	Moderate	Moderate	Major
Inset Lap	$E_1 = E_2$	Major	Minor	Major
	$E_1 > E_2$	Major	Minor	Major
Beveled Inset Lap	$E_1 = E_2$	Moderate	Minor	Major
	$E_1 > E_2$	Moderate	Minor	Major
Reinforced Lap	$E_1 = E_2$	Major	Major	Major
	$E_1 > E_2$	Major	Major	Major
Intermediate Lap	$E_1 = E_2$	Moderate	Moderate	Major
	$E_1 > E_2$	Major	Major	Major

FIGURE 4-4.1-2. SOME DESIGNS FOR OFFSET LAP JOINTS[16]

(From Adhesive Bonding of Reinforced Plastics, by H. A. Perry, Copyright 1959, McGraw-Hill Book Company, Inc. Used by permission of McGraw-Hill Book Company, Inc.)





Joint	Rigidity of Adherends	Stress Concentrations Under: F	-F	M
Butt	$E_1 = E_2$	Major	Major	Major
	$E_1 > E_2$	Major	Major	Major
Scarf	$E_1 = E_2$	Minor	Minor	Major
	$E_1 > E_2$	Major	Major	Major
Offset Lap	$E_1 = E_2$	Major	Major	Major
	$E_1 > E_2$	Major	Major	Major
Strap	$E_1 = E_2$	Major	Major	Major
	$E_1 > E_2$	Major	Major	Major
Double Strap	$E_1 = E_2$	Major	Major	Major
	$E_1 > E_2$	Major	Major	Major
Recessed Double Strap	$E_1 = E_2$	Moderate	Minor	Major
	$E_1 > E_2$	Major	Minor	Major
Beveled Double Strap	$E_1 = E_2$	Minor	Minor	Minor
	$E_1 > E_2$	Moderate	Moderate	Moderate
Double Lap	$E_1 = E_2$	Major	Major	Major
	$E_1 >> E_2$ $E_1 t_2 = E_1 t_2$	Major	Major	Moderate
Solid Double Lap	$E_1 = E_2$	Major	Moderate	Major
	$E_1 > E_2$ $E_1 t_1 = E_2 t_2$	Major	Minor	Moderate
Double Butt Lap	$E_1 = E_2$	Moderate	Minor	Major
	$E_1 > E_2$	Major	Minor	Major
Double Scarf Lap	$E_1 = E_2$	Moderate	Minor	Major
	$E_1 > E_2$	Major	Minor	Major

FIGURE 4-4.1-3. SOME DESIGNS FOR COLINEAR LAP JOINTS[16]

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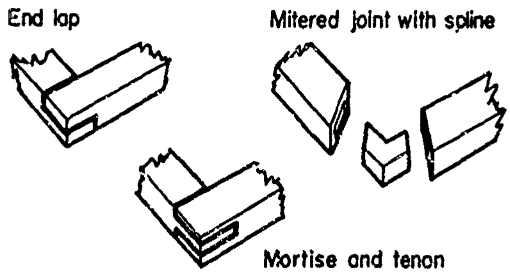


FIGURE 4-4. 1-4. CORNER-JOINT DESIGNS(17)

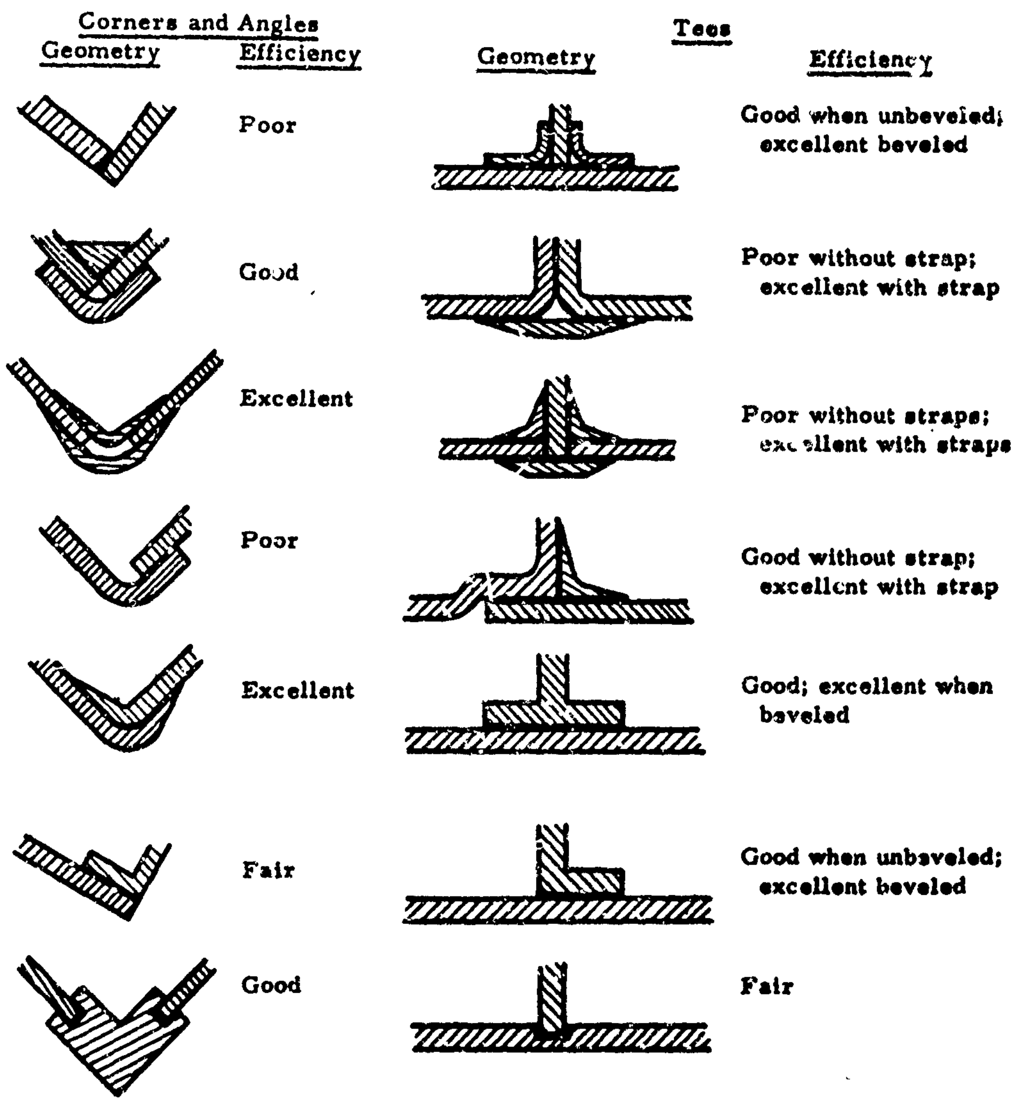
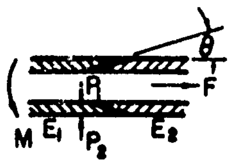
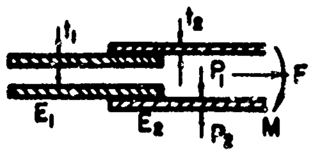
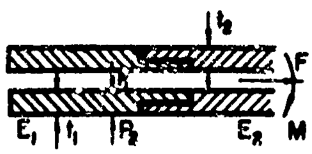
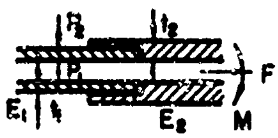


FIGURE 4-4. 1-5. SOME DESIGNS FOR EDGE, ANGLE, AND TEE JOINTS(16)

(From Adhesive Bonding of Reinforced Plastics, by H. A. Perry, Copyright 1959, McGraw-Hill Book Company, Inc. Use by permission of McGraw-Hill Book Company, Inc.)

	Rigidity of Adherends	F	-F	$P_1>P_2$	$P_2>P_1$	M
	$E_1 = E_2$	Minor	Minor	Minor	Minor	Minor
	$E_1 > E_2$	Major	Major	Minor	Major	Major
	$E_1 < E_2$	Major	Major	Major	Minor	Major
	$\frac{E_1t_1}{d_1} = \frac{E_2t_2}{d_2}$	Major	Major	Minor	Minor	Major
	$\frac{E_1t_1}{d_1} > \frac{E_2t_2}{d_2}$	Major	Major	Major	Minor	Major
	$\frac{E_1t_1}{d_1} < \frac{E_2t_2}{d_2}$	Major	Major	Minor	Major	Major
	$\frac{E_1t_1}{d_1} = \frac{E_2t_2}{d_2}$	Major	Minor	Minor	Minor	Major
	$\frac{E_1t_1}{d} > \frac{E_2t_2}{d}$	Major	Minor	Major	Minor	Major
	$\frac{E_1t_1}{d_1} < \frac{E_2t_2}{d_2}$	Major	Minor	Minor	Major	Major
	$\frac{E_1t_1}{d_1} = \frac{E_2t_2}{d_2}$	Major	Minor	Minor	Minor	Major
	$\frac{E_1t_1}{d} > \frac{E_2t_2}{d}$	Major	Minor	Major	Minor	Major
	$\frac{E_1t_1}{d_1} < \frac{E_2t_2}{d_2}$	Major	Minor	Minor	Major	Major

Stress Concentrations Under: F, -F, $P_1>P_2$, $P_2>P_1$, M

FIGURE 4-4. 1-6. SOME DESIGNS FOR TUBULAR JOINTS(16)

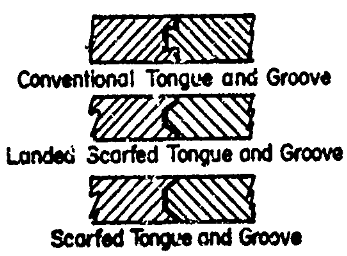


FIGURE 4-4. 1-7. BUTT-JOINT DESIGNS(18)

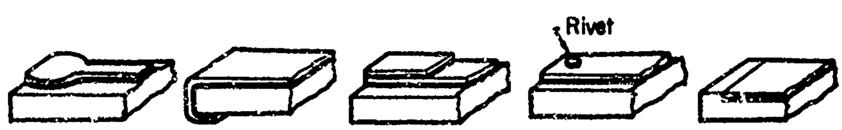


FIGURE 4-4. 1-8. PEEL-RESISTANT DESIGNS FOR FLEXIBLE MEMBERS(19)

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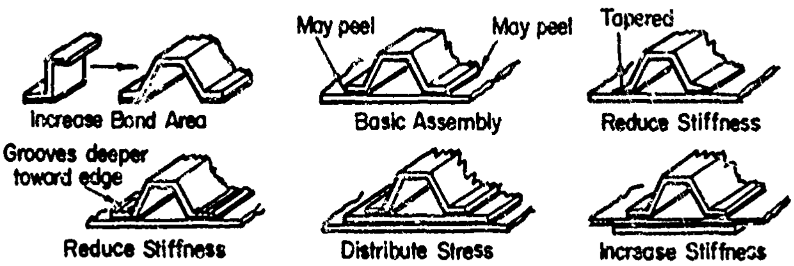

FIGURE 4-4. 1-9. JOINT DESIGNS FOR HAT-SECTION SKIN-AND-STRINGER CONSTRUCTION[20]

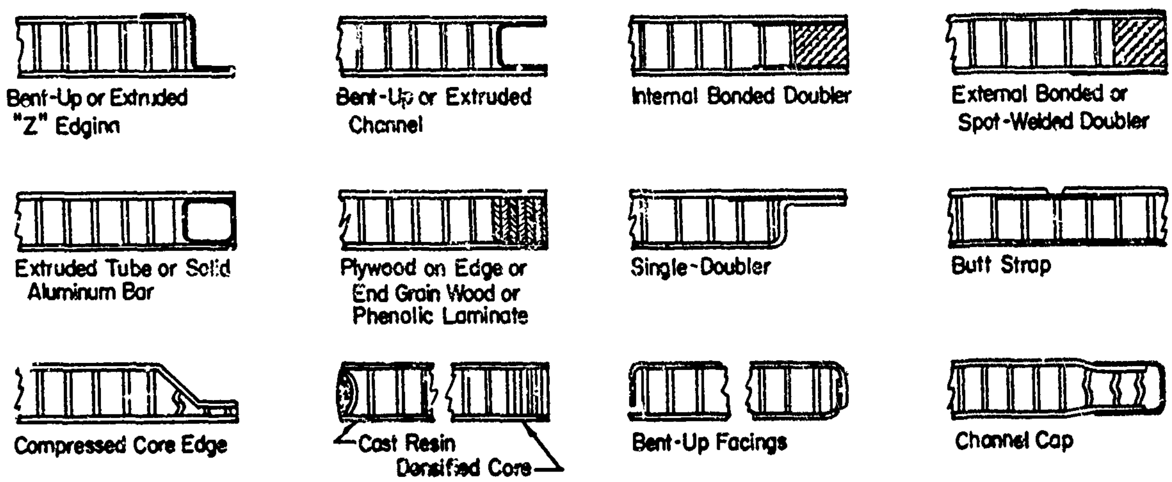

FIGURE 4-4. 1-10. HONEYCOMB-PANEL-EDGE DESIGNS[21]

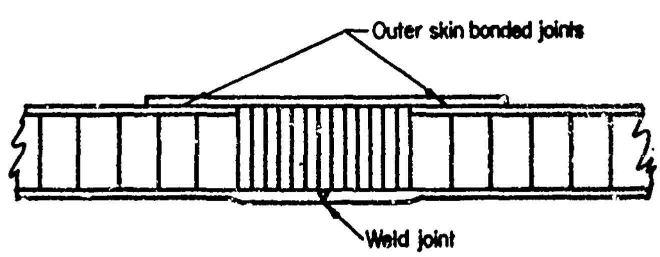

FIGURE 4-4. 1-11. CIRCUMFERENTIAL JOINT IN LARGE HONEYCOMB CYLINDER[22]

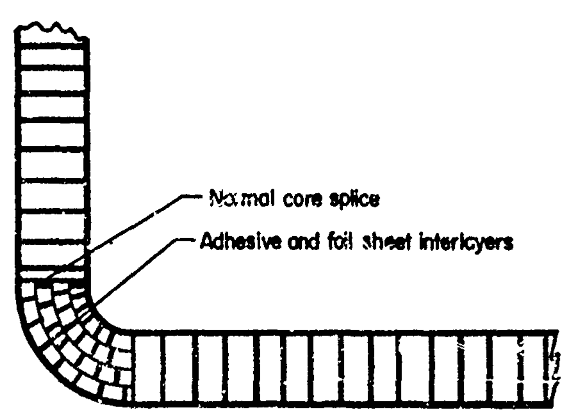

FIGURE 4-4. 1-12. DESIGN FOR A HONEYCOMB EDGE JOINT[27]

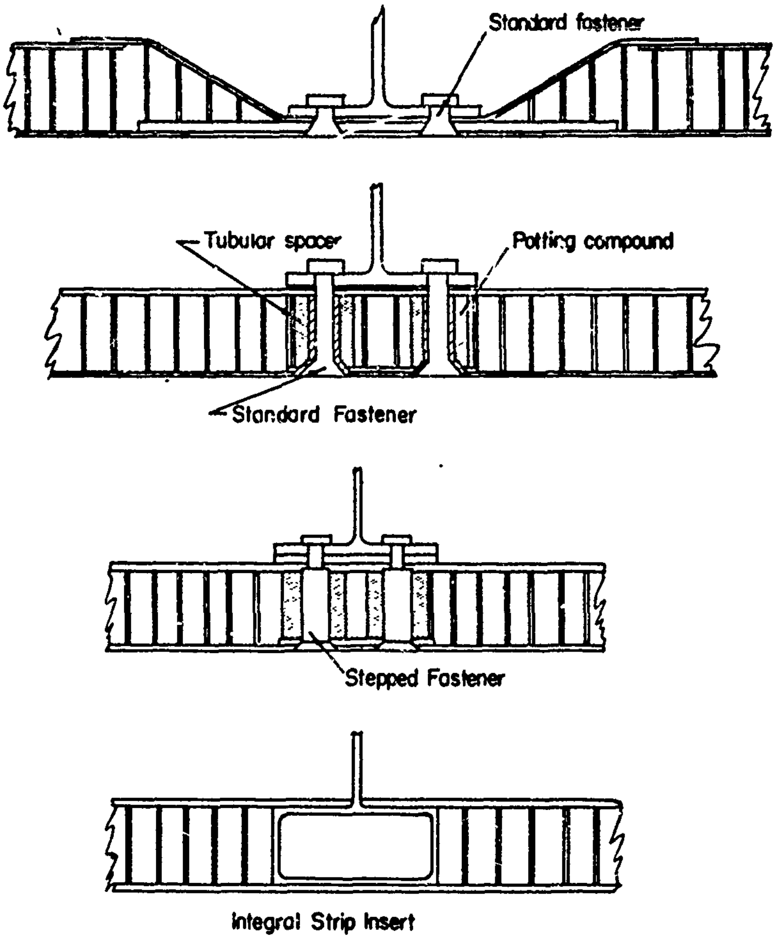

FIGURE 4-4. 1-13. METHODS OF ATTACHING PANELS TO SUBSTRUCTURE(27)

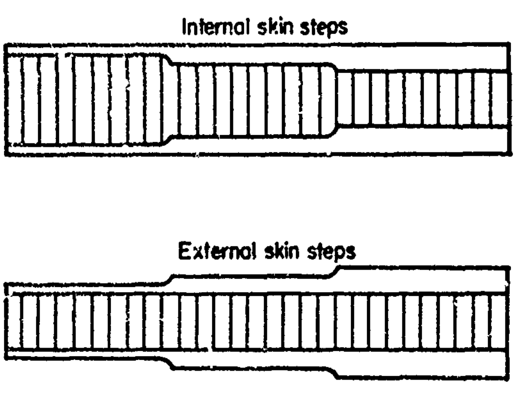

FIGURE 4-4. 1-14. INTERNAL VERSUS EXTERNAL SKIN STEPS(18)

The remaining figures show more complex structures. Hat-section skin-and-stringer panels are shown in Figure 4-4. 1-9. These designs allow good control over lateral stiffness of the joints through the use of doublers and changes in details of the stringer cross sections.

Honeycomb panel is becoming increasingly important as a lightweight, stiff structural design. A comprehensive handbook covering details of adhesive bonding of honeycomb has been published by the Armed Forces Supply Center.(15) Some typical edge closure designs that have been used with adhesively bonded honeycomb panels are shown in Figure 4-4. 1-10

Certain honeycomb structures require continuous-core construction or sharp bends. The design of these structures is difficult; some designs that have been used are shown in Figures 4-4. 1-11 and 4-4. 1-12. Figure 4-4. 1-13 shows some methods of attaching panels to substructures. Other recent honeycomb sandwich designs have made it necessary to use a stepped skin, as shown in Figure 4-4. 1-14. According to one source,(18) external steps are preferable to internal steps from the standpoint of obtaining a reliable core-to-skin bond. Internal steps require a contoured core, and tolerance mismatches in layup are likely. These mismatches will result in voids or crushed regions in the core. The external steps, shown

as being integral with the skin in the figure, might also be in the form of bonded double sheets.

4-4. 2 ADHESIVE PROPERTIES

There are presently hundreds of commercially available adhesives. Probably no two adhesives manufactured by different companies are exactly alike. For example, there are reportedly over 100 different curing agents for epoxy resins, each of which imparts something of its own characteristics to the adhesive. However, the only adhesives known to have been used with titanium belong to the class known as thermosetting adhesives.[1] These adhesives are chemically changed during curing so that they cannot melt or be dissolved in the common solvents. When overheated, they tend to char. The chemical change consists of cross linkages between resin molecules that from three-dimensional polymer networks. Thermosetting adhesives are the strongest class of adhesives and the only ones worthy of consideration for high-temperature applications. The following types of thermosetting adhesives are known to have been used for bonding titanium alloys:

Adhesive Type	Reference
Epoxy	12
Alloyed epoxy	12
Epoxy-silicone	12
Epoxy-phenolic	4,12,22,23,24,25
Epoxy-polysulfide	26
Epoxy-polyimide	24
Epoxy-nylon	24
Modified phenolic	12
Nitrile-phenolic	4,27,28
Vinyl-phenolic	23
Polyester	26
Polyurethane	24

4-4. 2. 1 Physical Forms

Metal-bonding adhesives are most commonly used as liquids, films, or tapes. Some of the thicker liquid types are thixotropic*, which is an aid in maintaining proper positioning of adherends following adhesive application but prior to curing. Adhesive films and tapes offer easy control of bond-line thickness and convenience of handling. The particular form of adhesive used for a specific application will depend on the joint area to be bonded, the production volume, the types of equipment on hand, and the forms in which the selected adhesive is available.

*Thixotropic materials are viscous if allowed to stand undisturbed, but temporarily decrease in viscosity after they are stirred or otherwise agitated. On standing, they revert to their former gelled state.[1]

4-4. 2. 2 Working and Storage Requirements

A decision to be made in adhesive selection, if an epoxy is chosen, is whether to use a one- or two-part adhesive. A two-part epoxy adhesive consists of resin and the curing agent. Until they are mixed, the two parts can be stored almost indefinitely at room temperature. Once mixed, however, the working time is only minutes or hours, depending on the ratio of the parts and the specific curing agent used. If these adhesives are not applied during the working time, they will have cured to the point that they are too stiff to apply. They do have the advantage of curing at room temperature, which eliminates the need for special curing equipment. However, unless they are postcured at elevated temperatures, their properties are inferior to those of heat-cured epoxies.[1]

One-part epoxies and phenolics are compounded mixtures of resin and curing agent and have a limited shelf life. They must be cured at elevated temperatures. The usual shelf life of commercially available adhesives of this type ranges from 6 months to a year at room temperature. This can be extended by storing in a freezer or refrigerator.

Polyimide-based adhesives, which are very promising for high-temperature titanium use as discussed later, have a particular handling requirement. In the uncured state, this adhesive is very sensitive to humidity and should not be exposed to relative humidity in excess of 30 percent.[2]

4-4. 2. 3 Service Conditions

No single adhesive is available that is superior for all service conditions. A user, therefore, makes a selection among possible adhesives on the basis of known or anticipated service conditions for the application.

4-4. 2. 3. 1 High Temperature

As shown in Figure 4-4. 2. 3. 1-1, adhesive strength decreases with temperature. Although it is difficult to place precise upper limits, phenolic and epoxy adhesives appear to be limited to temperatures in the vicinity of 350 F for continuous service with titanium. However, they can withstand temperatures up to 500 F for short times. Recent reviews dealing with high-temperature adhesives do not refer to titanium, but it is believed that all available titanium alloys can be bonded with any of the adhesives discussed. However, a particular adhesive gives different tensile-shear-strength values when used to bond different materials, as illustrated in Figure 4-4. 2. 3. 1-2. Consequently, it is not safe to assume, without testing, that titanium bonds will have the same strength values as stainless steel bonds.

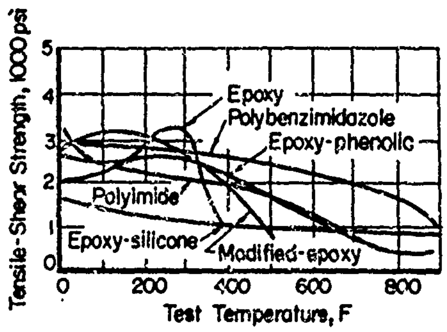

FIGURE 4-4.2.3.1-1. TEMPERATURE DEPENDENCE OF SHORT-TIME TENSILE-SHEAR STRENGTHS OF VARIOUS CLASSES OF ADHESIVES[29]

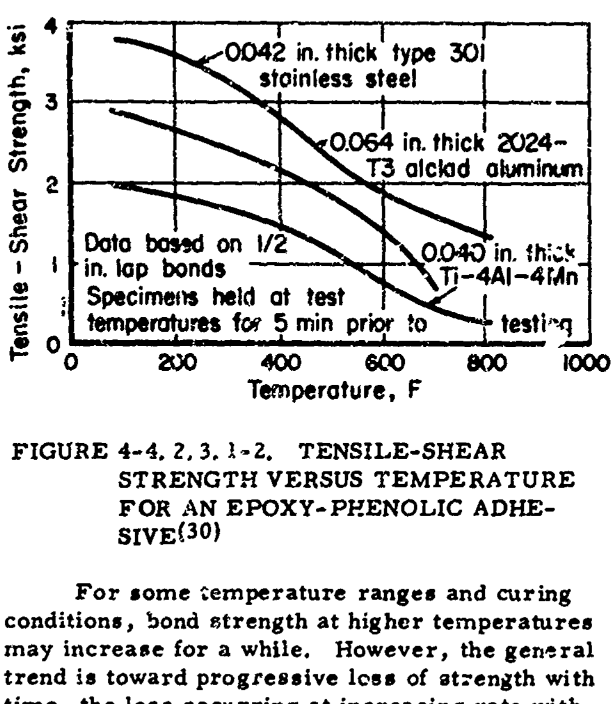

FIGURE 4-4.2.3.1-2. TENSILE-SHEAR STRENGTH VERSUS TEMPERATURE FOR AN EPOXY-PHENOLIC ADHESIVE[30]

For some temperature ranges and curing conditions, bond strength at higher temperatures may increase for a while. However, the general trend is toward progressive loss of strength with time, the loss occurring at increasing rate with increasing temperature.[29] Figure 4-4.2.3.1-3 shows losses in bond strength for three nitrile-phenolic adhesives used to bond adherends of Ti-5Al-1.25Fe-2.75Cr alloy.[4] Strength loss following 100 hours' exposure at 500 F was about 50 percent. When exposed at 600 F, loss of strength for these and other adhesives was very rapid.

Oxidation by atmospheric oxygen is the major factor causing degradation of organic adhesives at high temperatures.[1] In titanium, oxygen is highly soluble, the rate of oxygen transport at elevated temperatures is high, and adhesive degradation is thus accelerated. In certain experiments, for example, Boeing found that adhesive systems which had lasted for 7000 to 8000 hours with aluminum lasted only 500 hours with titanium.[31] Boeing has developed a proprietary surface-preparation process for titanium that has now increased the useful life of an adhesive to 3000 hours. The process is based on the principle of creating an oxygen-diffusion barrier at the adherend-adhesive interface.

Two new metal-bonding adhesives now on the market offer promise for use with titanium in the SST program. These are the polybenzimidazoles (PBI) and the polyimides (PI). The former appear useful for long-time service above 350 F and for short times above 500 F. The short-time tensile-shear strengths of these two adhesives can be seen in Figure 4-4.2.3.1-1.[29] However, polyimides have recently been developed that exceed these strength figures. These adhesives exhibit room-temperature lap-shear strengths of approximately 3400 psi on titanium and strengths of approximately 2000 psi at 500 F, even after several thousand hours. These adhesives generally contain an arsenic-based antioxidant that degrades rapidly at 600 F.[2]

There are several references in the Russian literature to high-temperature strengths of adhesive-bonded titanium joints. Among the more promising of these reports, Reference (32) cites tensile-shear strengths of 600 psi at room temperature and 500 psi at 798 F using VK-2 organosilicon adhesives. Other workers[3] report higher strengths for the same adhesive at like temperatures -- 950 and 670 psi, respectively. These investigators also report tensile-shear strengths of 1320 psi at room temperature and 570 psi at 798 F using VK-6 modified organosilicon adhesive. In other work,[33] bonded titanium adherends with a nitrile-phenolic adhesive blend reportedly showed tensile-shear strengths between 2650 and 3270 psi at room temperature and between 995 and 1565 psi at 392 F.

4-4.2.3.2 Radiation

Although there are several varieties of radiation, most organic materials are affected in much the same way by all varieties. Organic materials as a class are more radiation sensitive than metals and ceramics. The damage mechanism in these organic materials consists of the transfer of large amounts of energy to electrons within the material by their interaction with the incident radiation. Radiation damage to an adhesive shows up first as a loss of peel strength.[1]

Radiation effects should be relatively independent of the adherend material, except where the adherend itself becomes radioactive. In fact, the adherends offer a degree of protection against soft radiation. So, although the studies found on effects of radiation on adhesives do not concern titanium adherends, the conclusions should be applicable to titanium.

Typical behavior of the tensile-shear strength of several adhesives bonded to aluminum adherends

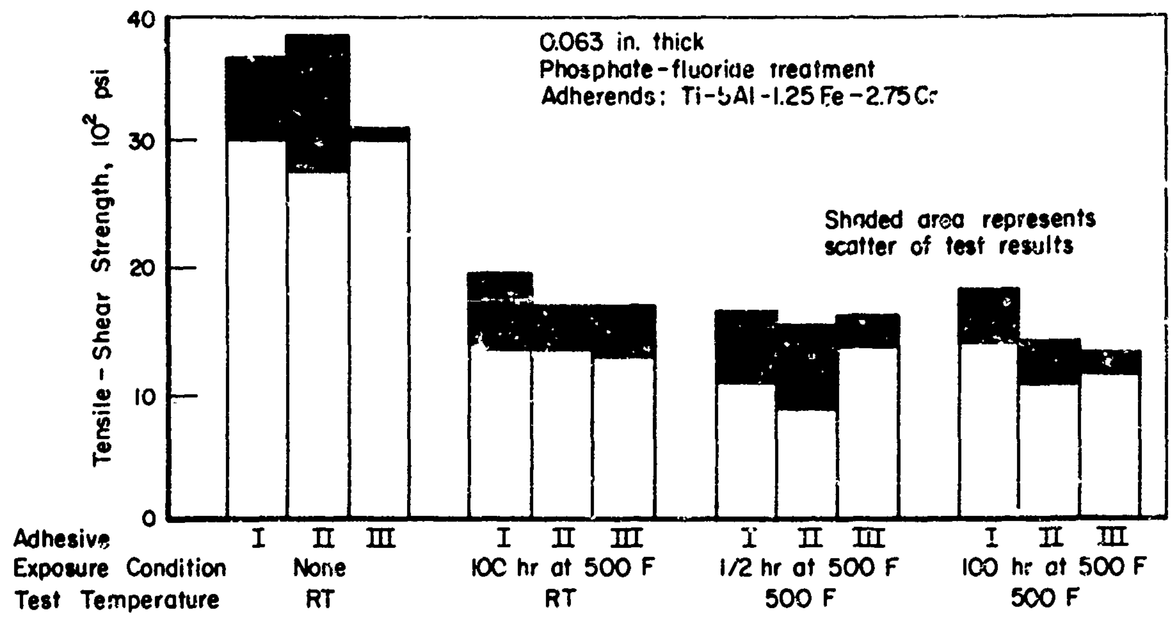

FIGURE 4-4.2.3.1-3. EFFECTS OF TEMPERATURE AND TIME OF EXPOSURE IN AIR ON TENSILE-SHEAR STRENGTHS OF ADHESIVE JOINTS USING TITANIUM ADHERENDS AND THREE NITRILE-PHENOLIC ADHESIVES(4)

with increasing amounts of gamma radiation are shown in Figure 4-4.2.3.2-1. These specimens were tested at room temperature. Most of the adhesives showed continued loss of strength as radiation increased. For specimens tested at elevated temperatures following irradiation, the order of ranking of the adhesive strengths is somewhat different.(34)

As shown in Table 4-4.2.3.2-1, thick glue lines are less susceptible to damage from gamma radiation as measured by tee-peel strength.(35) In this work, aluminum and stainless steel adherends were bonded with a nitrile-phenolic adhesive. In addition, a severe loss of peel strength following irradiation was also found for honeycomb panels made with composite film adhesives. In these structures, a glass-cloth carrier was coated, on the face sheet side, with a flexible adhesive for peel strength and, on the core side, with a more rigid adhesive that had better filleting characteristics. Adhesion failure occurred on the core side.

The new heterocyclic adhesives, such as the polybenzimidazoles, should be less radiation sensitive than types heretofore available. Adhesives are not presently available that can withstand the intense radiation found in the immediate vicinity of nuclear reactors, however.

4-4.3 ASSEMBLY CONDITIONS

Actual assembly of an adhesive-bonded joint involves applying the adhesive, positioning and holding the adherends in the desired relationship and curing.

4-4.3.1 Adhesive Application

The method of application depends on the form of the adhesive and the production rates desired. Thick liquid adhesives can be applied by roller coating, brushing, troweling, or dip coating. Thinner liquids can be sprayed, flow coated, or brushed on. If the adherend is laid out on a heated table, tapes and films can be applied by hand. If the table is not heated, a tacking iron is used in spots to cause enough adhesion to hold the adhesive in place. Adhesives in powder or stick forms do not appear to be widely used in this country for metal-to-metal adhesive bonding.(1)

4-4.3.2 Tooling and Fixturing

Clamping the adherends in proper position is most often necessary when bonding with adhesives, such as polyimides, that release water, solvents, or other volatile substances during curing. It may be necessary to apply pressures up to several hundred psi in these cases. Such curing pressures are not generally necessary with adhesives such as epoxies, classified as "100 percent solid". The exception in this case is critical work that may require clamping for control of glue-line thickness and alignment. There are several methods of applying pressure, and the one chosen will depend on the size and shape of the part, the amount of pressure to be applied, and the quantity of parts to be produced. The simplest method is to design self-clamping adherends. Another method is to combine adhesive bonding with another fastening method such as riveting. For parts with simple shapes, deadweight loading can be used.(1)

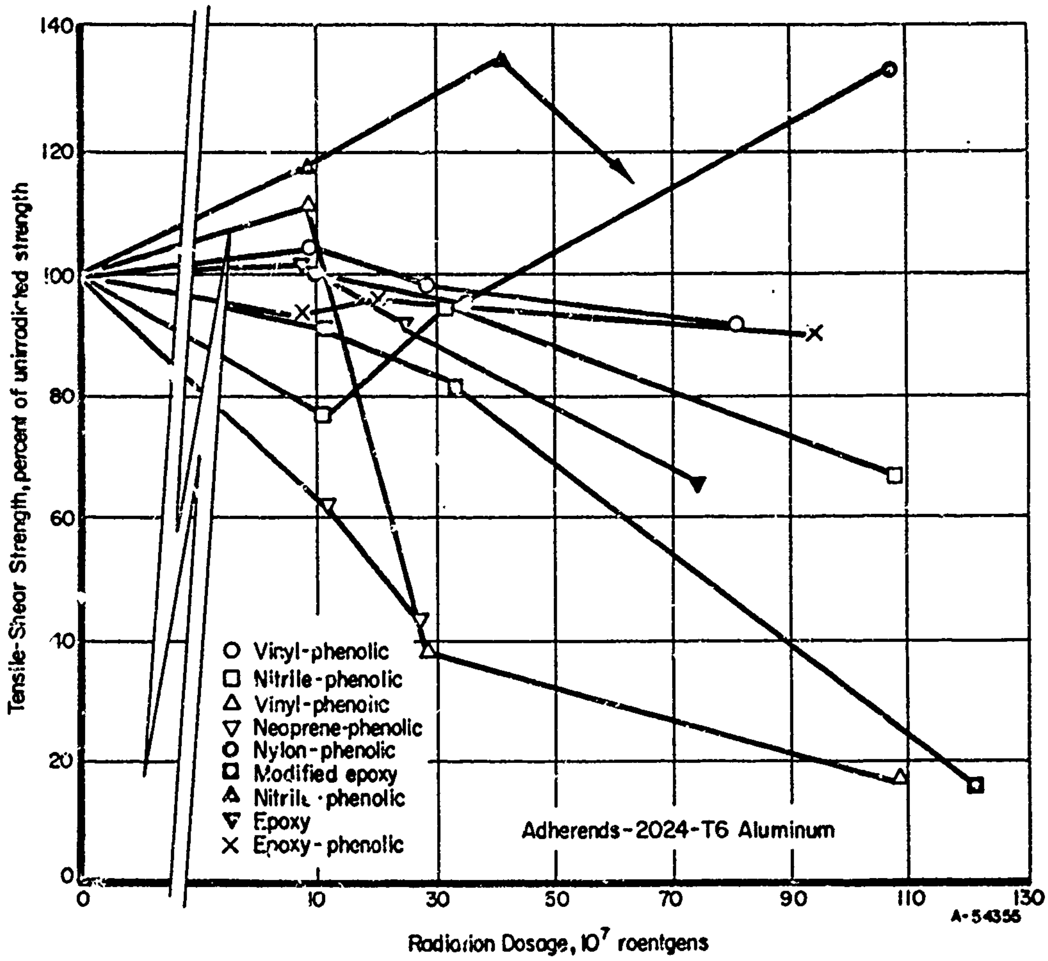

FIGURE 4-4. 2. 3. 2-1. TENSILE-SHEAR STRENGTH VERSUS RADIATION DOSAGE(34)

Specimens tested at room temperature.

TABLE 4-4. 2. 3. 2-1. EFFECT OF GLUE-LINE THICKNESS ON TEE-PEEL STRENGTH OF A NITRILE-PHENOLIC ADHESIVE WITH RADIATION EXPOSURES(35)

Glue-Line Thickness, mils	Tee-Peel Strength at Indicated Dosage, in.-lb/in.				
Radiation Dosage, megarads:	None	100	300	600	900
1.2	10	7	5	3.5	2.5
3.7	14	9	7	4	2.5
10.0	30	20	9	3.7	3.5
16.1	19	14	6	4.5	3.5

Several methods of clamping that require special tooling are shown in Figure 4-4. 3. 2-1. (15) The vacuum-bag technique, shown in Figure 4-4. 3. 2-1(a), can be used with parts have more complex shapes, but is limited to pressures below 14 psi. The pressure-shell method shown in Figure 4-4. 3. 2-1(b), can be used when higher pressures are needed. The pressure with this method is limited only by the mechanical design of the confining parts. The method can also be used with oven curing, as shown with the vacuum-bag method. Likewise, the vacuum-bag method can be used with a heated mold.

A more elaborate method is shown in Figure 4-4. 3. 2-1(c) -- the autoclave method. In this method, the part is sealed into a flexible blanket assembly, vented to atmosphere, that applies a differential pressure. It uses a hot inert-gas atmosphere under forced circulation. This type of mold is used when it is not necessary to maintain the maximum degree of smoothness on one side of the bonded assembly. However, when the exterior surface must meet stringent aerodynamic requirements, as with an aircraft skin, a rigid mold must be used for the exterior, and all tolerance mismatches must be taken up on the interior side of the panel. In some cases, both surfaces of a bonded assembly must meet smoothness and shape requirements, and tolerances must

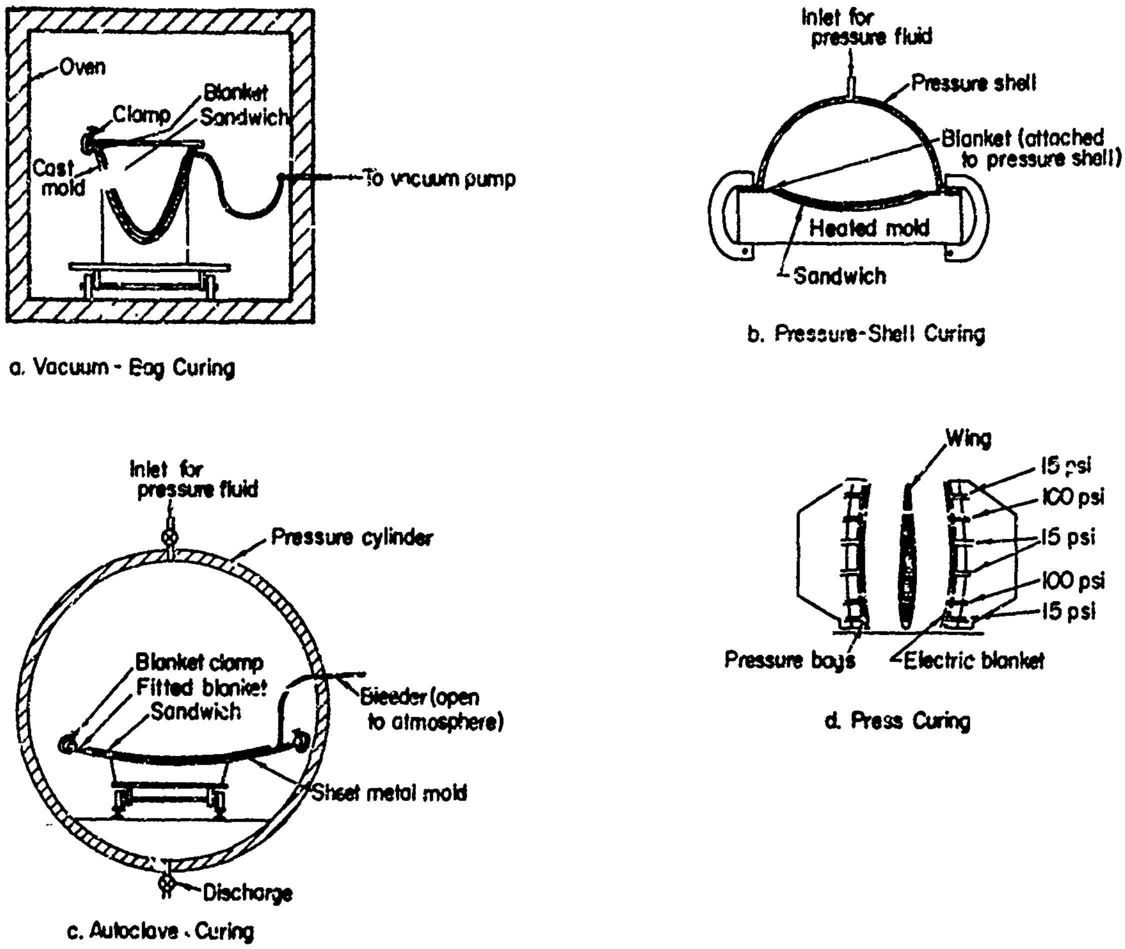

FIGURE 4-4.3.2-1. METHODS FOR CURING ADHESIVE-BONDED ASSEMBLIES[15]

be held very closely. In these cases, heated presses, as shown in Figure 4-4.3.2-1(d), are used.

4-4.3.3 Curing

In general, the curing conditions recommended by the adhesive manufacturer will result in bonds of optimum quality for a given application. However, when maximum properties are important, development work by the user may result in better quality through more complex curing cycles.

When room-temperature-curing adhesives are used, care should be taken that the working life has not been exceeded before use. It is also important to keep the volume of adhesive small. Considerable heat is often generated during curing. These adhesives do not usually have strength properties as good as adhesives cured at elevated temperatures. However, their strength can be improved by postcure heat treatment.

Curing can sometimes be accomplished as part of another operation, such as during the baking of a painted or enameled part or in a dehydration oven. There are also several novel means of curing. Smith and Susman[36] reported slight increase over room-temperature-cured strengths through application of a 700-volt alternating potantial across an epoxy-polyimide metal-to-metal bond. North American Aviation[37] has developed a film adhesive containing an array of fine high-resistance wires. Current is passed through the wires for a sufficient time to accomplish the cure. Another novel approach is the use of an exothermic adhesive reaction mixture.[38]

Cleaning of the cured joint is not usually necessary. Any adhesive extruded from the bond line can be removed by scraping or single-point machining if necessary.

4-4.4 HYBRID JOINING METHODS

An interesting development that deserves increased attention is the use of adhesive bonding

combined with other joining methods. The Soviets have done considerable work on the combined use of adhesive bonding and spot welding. They have shown that the combined method increases fatigue strength over the fatigue strengths of joints made by either technique singly.[39] However, there is some difficulty in spot welding reproducibly through the adhesive,[40,41] and the alternative of spot welding first and introducing the adhesive by a syringe-like dispensing tool is slow and variable.

The use of adhesive bonding and riveting is a more practical technique at present and is being used in applications with metals other than titanium.

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4-5 Mechanical Fastening

4-5.0 INTRODUCTION

There are many means available to mechanically fasten joints. These include shrink-fitted parts, turbine-blade "fir trees", keys, spring retainers, screws, rivets, and bolts. The type of fastener used is usually determined by the expected loads and the type of loading the joint will meet in service. However, most of the design and production considerations necessary for mechanically fastening titanium and its alloys with bolts or rivets are applicable to joints using less common, specialized fasteners. Therefore, the discussion in this section is limited primarily to bolts and rivets. It should also be noted that although most mechanical fastening experience has been acquired with materials other than titanium, most of the techniques applicable to these materials also apply to titanium.

Mechanically fastening titanium joints offers several advantages over other joining methods.[1] These are:

(1) Methods of design and fabrication are well established

(2) Joints can be disassembled nondestructively

(3) The overall soundness of joints can be inspected visually

(4) Dissimilar metals can be easily joined

(5) There is less thermal damage to structures

(6) Equipment requirements are less expensive

(7) Less surface cleaning is required

(8) Less elaborate tooling is needed for assembly.

On the other hand, mechanically fastened joints present certain limitations compared to other joining methods, including:[1]

(1) Stress concentration

(2) Residual stresses

(3) Electrical conductivity

(4) Weight

(5) Gaskets required for seals

(6) Thickness limitations

(7) Irregular outside surfaces at times

(8) Galling tendency

Mechanically fastened joints differ from each other in joint design and in the type of fastener and means of assembly. Aspects of these differences are discussed in subsequent parts of this Section. Certain factors that apply to any mechanically fastened joint are discussed in the following paragraphs.

4-5.0.1 Galvanic Corrosion

As pointed out in Section 1-0.5.2.3, physical contact between titanium and some dissimilar metals can lead to galvanic corrosion. While galvanic effects are not likely to occur when titanium is contacting Monel and stainless steels, less noble metals such as aluminum alloys, carbon steels, and magnesium alloys may suffer accelerated attack when coupled with titanium. Accordingly, it is recommended that a material be tested under simulated-service conditions whenever its corrosion resistance is of importance and available information is limited. This may indicate negligible corrosion and eliminate the need to take preventive steps.

One means of avoiding or reducing corrosion in mechanical joints is coating of the parts with a paint or plastic. Zinc-chromate primers have been used on dissimilar joints composed of titanium and aluminum with good results.[3] Galvanic corrosion of dissimilar metals can also be prevented by complete insulation. The use of cadmium- or silver-plated fasteners should be avoided in elevated temperature application as these fasteners can lead to a form of stress-corrosion cracking.[4]

4-5.0.2 Salt Corrosion

As is discussed in Section 1-0.5, hot salt stress corrosion is more severe the higher the stresses and exposure temperature. Rivets and certain specialized fasteners are characterized by the requirement of one or more components to be capable of large plastic deformation. As a consequence of this deformation, high localized residual stresses will be present in addition to service loading. Thus, the potential exists in certain types of fasteners for hot salt stress corrosion cracking. Figure 4-5.0.2.1 shows some limited data obtained on rivets and bolts of different titanium alloys. In this figure, all curves represent the minimum values for given conditions. The data on bolts of Ti-6Al-4V alloy show a reduction in tensile strength of about 9 percent in 1000 hours of hot salt exposure at500 F. A comparable exposure period without salt resulted in about a 4 percent reduction. On the other hand, the

Ti-7Al-12Zr al'oy · ·ved an increase in strength in the hot salt en· ·. ment as well as a co·nparable increase in s·.ength with the same elevated temperature exposure without salt.

Examination of the information on rivets, some of which is not shown in the figure, shows for three titanium alloys an overall reduction in strength, sometime during the 1000 hour period of unstressed hot salt exposure. Reductions of 5 percent, 36 percent, and 13 percent for Ti-75A, Ti-13V-11Cr-3Al, and Ti-4Al-4Mo-4V were observed, respectively. As with the bolts, the reductions partly were a consequence of the exposure at 500 F.

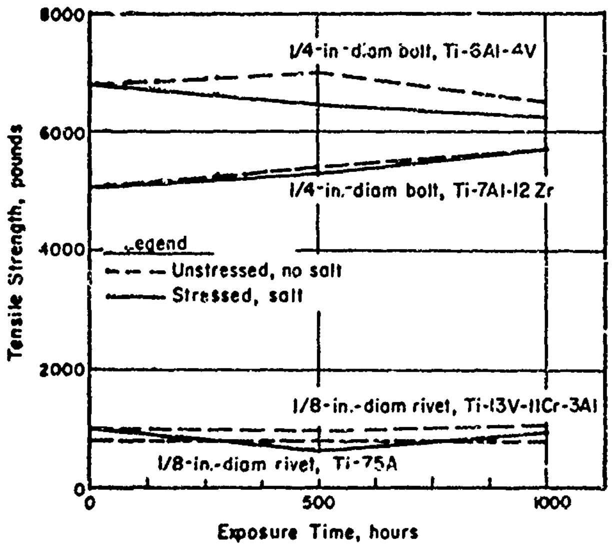

FIGURE 4-5.0.2-1 EFFECT OF EXPOSURE AT 500 F ON TENSILE STRENGTH OF TWO TYPES OF FASTENERS

Another way of looking at test results is to record under the test conditions when cracking of the sheet or fastener occurs. A series of tests not yet completed, including spot welds and fusion welds in addition to mechanical fasteners, can illustrate the care that must be exercised in selecting joining methods if this problem in the actual airplane environment is real. The results of tests on a series of specimens made from various titanium alloys are summarized in Table 4-5.0.2-1. In this table, it can be seen that countersunk rivets in Ti-8Al-1Mo-1V sheet become cracked in less than 400 hours, whereas the basic material of spot welded and fusion welded joints is uncracked after almost 2000 hours. The data on Ti-5Al-2.5Sn are quite premature to show possible problems except for rivets, where cracking appears at 96 hours' exposure. With either heat treatment of Ti-13Cr-11V-3Al, early cracking of spot welds, fusion welds, and mechanical fasteners occurred, even though tests on the basic material were continuing after 1464 hours.

4-5.0.3 Stress Concentration

The load across a mechanically fastened joint is concentrate at each mechanical fastener. Joint strength is also reduced by the removal of metal for holes or fastener bearing surfaces. This stress concentration has already been mentioned as one of the limitations of mechanical fastening.

At Boeing, a factor called "net area efficiency" is used to account for both holeout and stress concentrations in the sheet This is the ratio, determined by test, of the strength of drilled sheet and/or sheet tension critical joints to the strength of undrilled specimens cut from the same sheet.[5]

4-5.0.4 Residual Stresses

Another limitation is the residual stresses inherent to a mechanically fastened joint. These can be created in the permanent deformation of fasteners or of the joint under the fasteners. Machining may also leave high, localized residual stresses. Operations such as dimpling or joggling create high residual stresses unless the parts are heat treated after assembly.

4-5.0.5 Seals

Mechanically fastened joints are not inherently leak-proof and generally require a gasket-either an organic coating or an elastomer. The elastomer seals are available with moderate service life at moderately elevated temperatures. The upper temperature limits of the better sealing materials are just below the temperature range where use of titanium becomes most attractive.[1]

The fatigue life of a joint will decrease where gaskets of lower modulus of elasticity than the two structural parts are used.[1] The stiffness of the joint is also decreased with the use of a gasket. Where gaskets are used with thin plate, bolt preload must be carefully selected. Either underloading or overloading will allow leakage, the latter due to buckling of the gasket.

4-5.0.6 Galling

Where titanium surfaces slide across one another, galling or "cold welding" results. This is due to the high coefficient of sliding friction, the low thermal conductivity, and the high reactivity of titanium. Thus, a lubricant should always be used with titanium surfaces in sliding applications. Sulfides of tungsten or molybdenum have been used successfully to prevent galling. Because of the galling between threaded fasteners and nuts when both are of titanium, steel and aluminum nuts are generally used, with titanium bolts. However, it is understood that materials are now availabe for use on threads that allow bolts and nuts to be removed and reinstalled without excessive galling even after repeated exposure to elevated temperature

TABLE 4-5.0.2-1. EFFECT OF HOT SALT CORROSION ENVIRONMENT ON CRACKING OF VARIOUS TYPES OF SPECIMENS

	Exposure Time, hours for first cracking, and Type of Crack				
Coupon Type	Ti-8Al-1Mo-1 at 500 F	Ti-5Al-2.5Sn at 500 F	Ti-5Al-2.5Sn at 650 F	Annealed Ti-13Cr-11V-3Al at 500 F	Ti-13Cr-11V-3Al at 500 F
Plain tension	1968, test continuing	192, test continuing	192, test continuing	1464, test continuing	1464, test continuing
Spotwelding, bending	Ditto	Ditto	Ditto	96 scab cracks	96, scab cracks
Countersunk rivet	384, rivet cracks	96[a], test continuing	96, test continuing	96, scab and rivet cracks	96, rivet cracks
Dimpled rivet, bending	192, rivet cracks	96, one specimen with rivet crack	Ditto	384, scab and rivet cracks	384, rivet cracks
NAS screw, bending	--	96, test continuing	"	576, scab cracks	960, scab cracks
Fusion welding, bending	1968, test continuing	192, test continuing	"	96, weld cracks	96, weld cracks

(a) Rivets with no load had cracks at 96 hours.

4-5.0.7 Inspection

The overall soundness of a mechanically fastened joint can be inspected readily by simple visual examination. However, the careful inspection of machined parts prior to assembly is also essential. The use of a dye-penetrant inspection at intermediate stages of fabrication is highly recommended to prevent the subsequent processing of a defective, cracked product. Preloaded bolts can be checked at random to determine whether the product has been properly assembled. For certain parts, additional fatigue, bending, or tensile tests may be required.[1]

4-5.0.8 Specifications

Specifications applying to titanium fasteners are listed in Table 4-5.0.8-1. In addition to these, and of particular importance, is the Society of Automotive Engineers Aeronautical Materials Specification AMS-7469, issued in 1960. This is intended for bolts for use at temperatures up to 750 F. The specification details the acceptable dimensional tolerances and metallurgical properties, and specifies the flow-line appearance.

4-5.1 JOINT DESIGN

Numerous handbooks are available that cover standard practices for the design of bolted and riveted joints. There are many fasteners commercially available, either made of titanium or suitable for use with titanium. These are listed in manufacturer's catalogs and include those made of pure titanium, several titanium alloys, A 286 alloy, and monel. A detailed handbook[6] tabulates the dimensions of commonly used fasteners. The following paragraphs discuss some general aspects of mechanically fastened joint design as they apply to titanium joints.

4-5.1.1 Types of Loading

One classification of mechanically fastened joints considers whether the fastener is loaded in tension or shear. In a well-designed joint, all joint members are in balance, and failure may occur in the joint members or fastener. The strength of mechanical joints is in part related to the strength of the individual fasteners. For this reason, it is necessary to know the strength of the various types of fasteners. In certain kinds of joints, where fasteners are predominantly loaded in shear, joint failure may occur by shearing of the fastener or by bearing or tearing of the sheet or plate. However, in practice there is a strong tendency to avoid shear critical joints in sheet metal.[5] This is due primarily to a desire to avoid "zipper" failure of long joints. This type of failure occurs in long joints due to uneven loading and a resultant progressive shear failure of one fastener at a time. This can be prevented by using bolts at each end of a long run of rivets. In joints or fittings where the fastener is subjected primarily to tensile forces, joint failure may be a tensile or fatigue failure of the fastener or may be a failure of the fitting. Thus, fastener sizes and spacing should be chosen with consideration for the thickness and properties of the materials being joined and for the expected loading. Several basic equations can be used in choosing fastener and joint designs:[7]

Fastener shear load:

$$P_s = S_s A_n ,$$

Fastener load in tension.

$$P_t = S_t A ,$$

TABLE 4-5.0.8-1. STANDARDS FOR TITANIUM-ALLOY FASTENERS(1)

Fastener	Type	Specification
Threaded Bolts		
Hex Head, Close Tolerance	Short Thread	NAS 563-568(2)
		NAS 1261-1265
		NAS 1266-1270(2)
	Long Thread	NAS 673-678(2)
		NAS 1266,1268
		NAS 663-667
100-Degree Flat Head, Close Tolerance	Short Thread	NAS 1083-1088(2)
		NAS 663-668(2)
Twelve Point	External Wrenching	NAS 1271-1280(2)
Bolts and Screws (Ti-6Al-4V) Heat Treated	Roll-Threaded	AMS 7460A
Bolts and Screws (Ti-6Al-4V) Upset Headed, Heat Treated	Roll-Threaded	AMS-7461
Lockbolts		
Lock, Shear, 100-Degree Head	Pull Type	NAS 2506-2512(2)
	Stump Type	NAS 2706-2712(2)
Lock, Tension, 100-Degree (AN509) Head	Pull Type	NAS 2106-2110(2)
	Stump Type	NAS 2306-2310(2)
Lock, Tension, Protruding Head	Pull Type	NAS 2006-2010(2)
	Stump Type	NAS 2206-2210(2)
Lock, Shear, Protruding Head	Pull Type	NAS 2406-2412
	Stump Type	NAS 2606-2612
Hi-Shear Rivets	100-Degree Interference Fit	NAS 1906-1916(2)
	Flat Head, Interference Fit	NAS 1806-1816(2)
General Fasteners, Titanium and Titanium Base Alloys, Design and Usage Limitations		MS 33592

Note: The procurement specification for all these fasteners is NAS 621.

Root diameter area:

$$Ar = 0.7854\left(D - \frac{1.3}{N}\right)^2$$

Bearing failure load:*

$$P_b = S_b A_b$$

or

$$P_b = S_b t D ,$$

Plate tensile strength:**

$$P_u = S_u (W - mD)t ,$$

where

A = Root diameter area of threaded section, in^2.

A_b = Area in bearing, in^2.

A_r = Effective cross-sectional area, in^2.

A_s = Tensile stress area of a threaded area, in^2.

D = Nominal diameter of fastener, in.

m = Number of rivets in transverse row

n = Number of shear planes

N = Number of shear threads per inch

P_b = Ultimate bearing strength of joint, lb

P_s = Fastener shear load, lb

P_t = Fastener load in tension, lb

P_u = Tensile failure load, lb

S_b = Ultimate bearing strength of plate, psi

S_s = Fastener shear stress, psi

S_t = Fastener stress in tension, psi

S_u = Ultimate tensile strength of plate, psi

W = Width of plate, in.

Because shear and tension allowables are expressed in pounds per fastener in MIL-HDBK-5 and most design manuals, fastener shear and tension formulas are not strictly necessary. At Boeing, the H-28 root areas (or their equivalent for MIL-S-8879 threads) are used.[5] These are

*This formula is not applicable to countersunk members, dimpled members or any members fastened with shear-head fasteners or fasteners with multiple piece shanks.

**This formula can be revised to include a factor N_n, the net area efficiency factor discussed in 4-5.0.3, to account for stress concentration around the holes.[5]

the only areas that can be used for bolts that will never result in allowables exceeding the specification requirements (See MIL-S-6812). Therefore, root areas used at Boeing are somewhat lower than those in MIL-HDBK-5 or those the formula would provide.

Rivets are generally used only in joints loaded in pure shear because tensile forces tend to pry the rivet away from joined parts. This causes serious loosening and consequent fatigue of the rivet. Threaded fasteners are used in both shear and tension loaded joints.

When minimum weight is desirable, titanium fasteners should be considered for shear loading. Recent strength tests give an indication of possible design properties.[3] Typical shear strengths of No. 10-1/4 inch bolts of Ti-7Al-12Zr ranged from 130 ksi at -400 F to 50 ksi at 800 F. Similar bolts of Ti-6Al-4V had typical shear strengths ranging from 155 ksi at -400 F to 65 ksi at 400 F. Currently available Ti-6Al-4V fasteners, per Table 4-5.0.8-1, are required by specification to develop a 95 ksi minimum shear strength at room temperature.

4-5.1.2 Joint Configurations

A number of basic designs for joints in flat sheet are shown in Figure 4-5.1.2-1.[1] In actual structures more complicated extensions of these joints would be used. Mechanically fastened joints of skin surfaces exposed to aerodynamic heating are made with one side flush. These joints could be joined with either rivets or threaded fasteners. Five common modes of failure in the mechanically fastened joint are illustrated in Figure 4-5.1.2-2.

Less common modes of failure involve failure of the fastener heads, nuts or collars and pulling the heads, nuts or collars through the sheet. These modes apply to the shear-head, flush-head and blind fasteners for which allowables must be determined by testing. The optimum joint strength may be attained by designing the joint elements with diameters, thicknesses, strengths and edge margins to provide equal strength in all modes of failure. Any single mode, and certain combinations, may be avoided by selection of characteristics to make the joint stronger in that mode or modes. Edge margins are usually one and one-half or two times the fastener diameter, but intermediate margins are permissable. In designs for impact or fatigue loading, sharp transitions and changes of section should be avoided.[6]

The fatigue strength of a threaded fastener can also be optimized by the use of high root radius threads per MIL-S-8879, a rolled head-to-shank fillet radius, and rolled threads. Rolling of the radius and threads after heat treatment is usually preferable.

4-5.1.3 Tension Fasteners

Tension fasteners are generally threaded fasteners and are best used where cyclic tensile stresses act upon a fastener. Proper selection of the fastener, design of the joint, and preload of the fastener will eliminate failure due to loosening, and increase the fatigue life of the joint. The highest stress on a fastener with the possible exception of high external loads occurs during tightening when torque is applied to overcome friction. Removal of the tightening torque leaves only the preload. By torquing above the yield point, the highest preloading capability is consistently attained. But this practice presents two limitations. First, the bolt cannot be reused. Second, imprecise control of the tightening torque may cause failure in materials such as titanium, where the ultimate tensile strength is not much higher than the yield strength. When bolts are used with a high preload, allowance should be made for thermal expansion forces and other external load conditions. Otherwise, permanent deformation of the bolt and a decrease in preload and joint life will result.[1]

4-5.1.4 Shear Fasteners

A preload joint can resist shear action when the clamping force across the joint is sufficient to prevent movement between the two parts. Titanium can be effectively clamped with smaller bolt loads than are used with other materials because of its high coefficient of surface friction. However, in air frames, shear-type fasteners are almost always used with comparatively low torques which do not develop great friction forces in essentially metal-to-metal contact in close-fitting holes.[5]

Shear joint criteria pertinent to the various fasteners are based upon joint test data. The ultimate load and yield load criteria are as follows for the various fastener categories:

(1) Rivets

(a) Ultimate load allowable is the average test ultimate load divided by 1.15. This 1.15 factor is not applied to the shear strength cut off.

(b) Yield load allowable is the average test load at which the following permanent set occurs across the joint:

(1) 0.005-inch up to and including 3/16-inch-diameter rivets

(2) 2.5 percent of the rivet diameter for all larger diameter fasteners

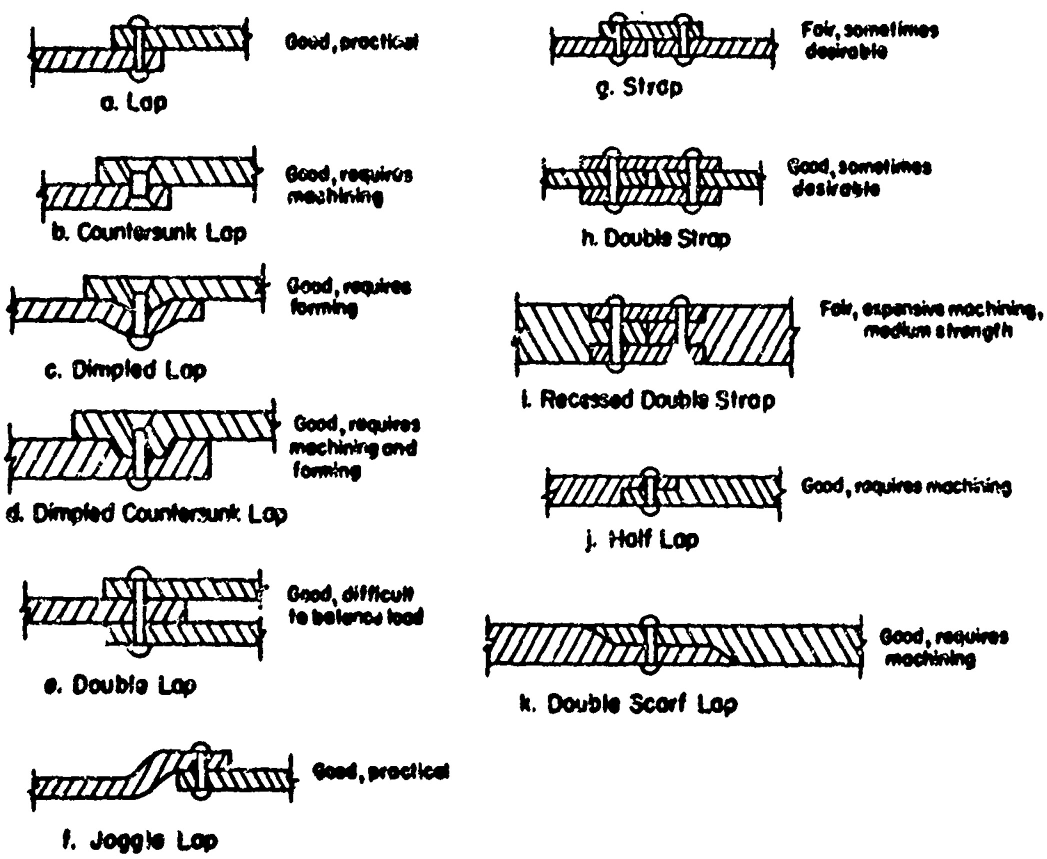

FIGURE 4-5.1.2-1. BASIC DESIGNS FOR JOINTS IN FLAT SHEET[1]

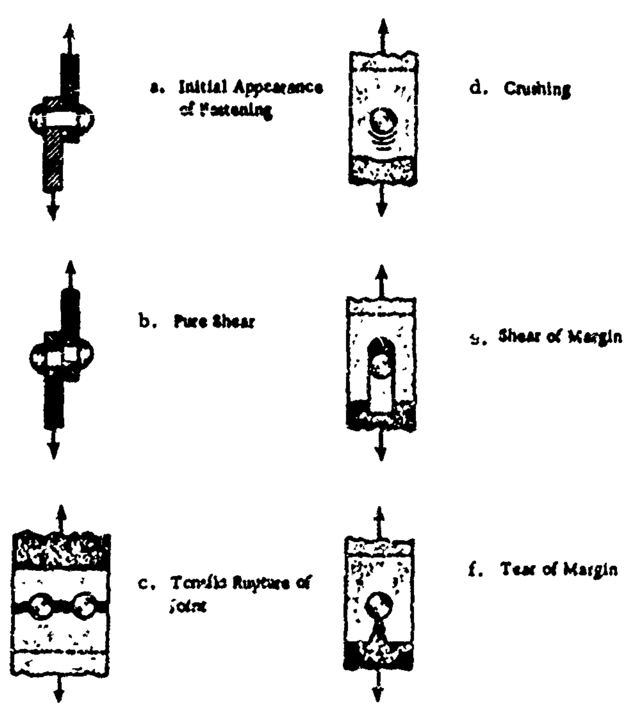

FIGURE 4-5.1.2-2 TYPES OF FAILURE IN SHEAR-LOADED, SHANK-TYPE JOINTS[9]

(2) Threaded fasteners

(a) Ultimate load - as stated for rivets

(b) Yield load - as stated for rivets, except that the permanent set is as follows:

(1) 0.012-inch, up to and including 0.250-inch-diameter fasteners

(2) 4.0 percent of the fastener diameter for all larger fasteners.

Rivet criteria are applied to all expanding-shank, hole-filling fasteners. The threaded-fastener criteria are applied to all non-expanding, non-hole-filling fasteners.

4-5.1.5 High-Temperature Design

The mechanical properties of titanium change with temperature. Figure 4-5.1.5-1 is a graph of short time tensile strength as a function of test temperature for a number of titanium alloy bolts. Plotted here is tensile strength in ksi, based upon the tensile stress area. On the basis of these curves it can be seen that up to 600 F (plus) temperature range, the all beta alloy is the strongest. However, next in strength is Ti-7Al-12Zr, which is better than the three other alloys at temperatures also in excess of 200 F.

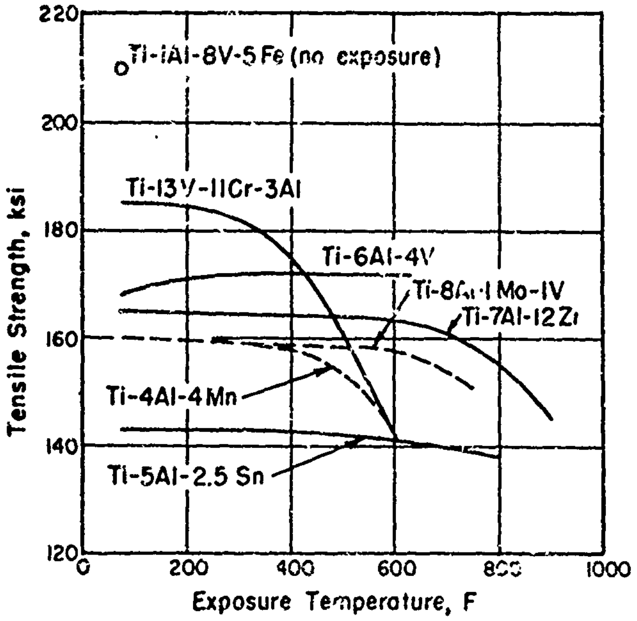

FIGURE 4-5. 1. 5-1 EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF TITANIUM BOLTS

Figure 4-5. 1. 5-2 is a graph of room temperature tensile strength after exposure times of either 10 hours or 100 hours at the indicated temperatures. Also shown on the graph is the room temperature strength of a fastener of Ti-1Al-8V-5Fe alloy, which currently is being considered only as a room temperature fastener.

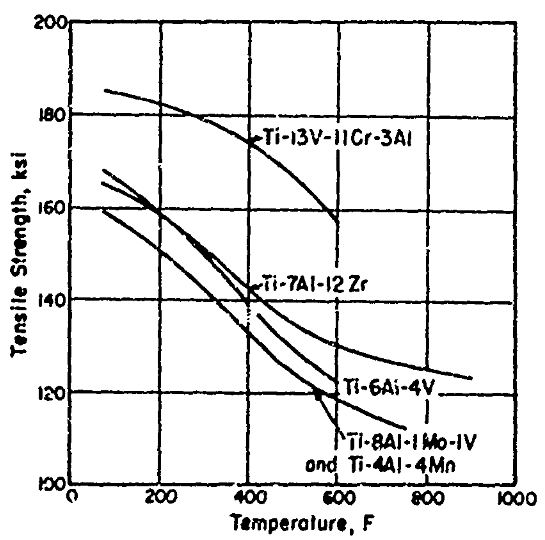

FIGURE 4-5. 1. 5-2 EFFECT OF 100-HOUR EXPOSURE AT TEMPERATURE ON ROOM TEMPERATURE STRENGTH OF TITANIUM FASTENERS

From this figure, it can be seen that the all beta alloy fasteners, judged the best on the previous figure, show a considerable amount of instability in the 400 F to 600 F range. As a matter of fact, the Ti-6Al-4V, Ti-7Al-12Zr, Ti-8A-1Mo-1V, and Ti-5Al-2.5Sn alloys appear to be least affected in the temperature range 400-600 F. All, however, show some tendency toward instability for times as short as 100 hours. It should be noted that these are insufficient exposure times to permit determination of design allowable strength values for joints and fasteners.

Table 4-5. 1. 5-1 summarizes scattered information available on axial load fatigue of tension fasteners made from various titanium alloys. Fasteners were tested at R = 0. 1 with a maximum stress of 83 ksi, or were tested at R = 0. 25 with a maximum stress of 77 ksi.

From the table, a number of facts emerge that are of interest. All fasteners when exposed at either 600 F or 750 F for as short as 100 hours had a reduction in fatigue life The best alloy in this regard (exposed at 750 F) was Ti-7Al-12Zr, which showed a life reduction of 5 percent. The largest reduction was 12:1 for the Ti-4Al-4Mn alloy, considered one of the better titanium fastener alloys at room temperature. Another fact to note is the large reduction in life at test temperature. In this case, the Ti-7Al-12Zr alloy shows the greatest loss.

Because the data available for study were very limited, the above discussion is of a qualitative, rather than a quantitative, nature. The establishment of design strength values will depend on further long exposure testing.

Titanium has a lower coefficient of expansion than most steels, stainless steels, and nickel alloys[3]. Thus, in high-temperature service, mechanically fastened joints between titanium and other metals will be subject to loosening and tightening of the fastener. Design allowance must be made for this fact. In most cases, the use of a higher fastener preload and careful selection of joint materials will eliminate any thermal loosening problems. Tightening is a problem only when the combination of the thermal stress with the preload and design load exceeds the yield point of the fastener. This will cause permanent deformation and loosening on subsequent cooling. High-temperature applications often must consider the decrease in preload that can occur because of relaxation of the bolt.

4-5. 1. 6 Low-Temperature Design

Many of the above design factors are equally important in considering low-temperature design. Some titanium alloys have satisfactory properties at low temperature, others do not. The differences in coefficient of expansion between titanium and other metals must be considered in low-temperature design. For example, it would be difficult to keep titanium fasteners tight in aluminum structures cooled to very low temperatures.

TABLE 4-5.1.5-1. EFFECT OF EXPOSURE ON FATIGUE LIFE OF VARIOUS TITANIUM-ALLOY FASTENERS

Titanium Alloy	Test Temp, F	Exposure Temp, F	Exposure Time, hours	Minimum Fatigue Lifetime, cycles	Average Fatigue Lifetime (4 Specimens), cycles	Maximum Stress[a], ksi
Ti-7Al-12Zr	RT	None		460,000	--	77
	RT	750	100	440,000	--	77
	750	None		35,000	--	77
Ti-8Al-1Mo-1V	RT	None		43,000	--	77
	RT	750	100	12,000	--	77
Ti-6Al-4V	RT	None		--	92,000	83
	RT	600	100	--	15,000	83
	600	None		--	16,000	83
Ti-4Al-4Mn	RT	None		--	403,000	83
	RT	600	100	--	31,500	83
	600	None		--	51,000	83
Ti-13V-11Cr-3Al	RT	None		--	45,000	83
	RT	600	100	--	9,000	83

(a) At 77 ksi, R = 0.25; at 83 ksi, R = 0.10.

4-5.2 FASTENER SELECTION

Titanium and its alloys are mechanically joined with the same type fasteners used for more conventional materials. Mechanical fasteners are available in a large number of sizes and shapes and with many functions. The type of fastener used is usually determined by the expected loads and the type of loading the joint will meet in service.[1] There are also many factors that determine the material from which the fastener should be made. If light weight is essential, titanium or aluminum fasteners should be used. If high strength is needed, the fastener may be made from high-strength steels, such as H11 or SAE 4340. For high-temperature service, A286 or another high-temperature alloy may be used. Where ease of forming is important, Monel may be used as a fastener material. There are also such factors as corrosion resistance and thermal expansion, as discussed earlier, to be considered.

Although application is a prime factor in selecting specific fasteners, such factors as cost, availability, equipment required, and previous shop experience must also be considered. Details of the latest features should be obtained from the manufacturers. Almost any fastener design can be obtained in titanium if the customer is willing to pay the price and wait for manufacture. Some considerations to be made when mechanically fastening titanium and its alloys with rivets and bolts are discussed above.[1]

4-5.2.1 Titanium Rivets

The current production and availability of titanium rivets is limited. However, commercially pure titanium rivets are available. Titanium rivets tend to work harden slightly during driving at room temperature. Lubrication of the rivet facilitates assembly of negative-clearance titanium rivets by preventing galling of the rivet in the hole.[1]

The results of some tests on mechanical properties for titanium rivet wire of several different alloys are shown in Table 4-5.2.1-1[1]. In addition to being tested for shear and creep properties, the materials were evaluated for heading and driving characteristics and for resistance to operating environment. Only Ti-3Al-2.5V was acceptable in all categories. Further development work is in progress on the higher strength materials. These alloys are being thermally processed to improve heading characteristics.

4-5.2.2 Non-Titanium Rivets

Non-titanium rivets, particularly Monel, have been widely used in titanium joints. Design allowables for such rivets are shown in Table 4-5.2.2-1. When these fasteners are being used, the effects of galvanic corrosion and differential thermal expansion should be accounted for in the design. Aluminum and steel fasteners are subject

TABLE 4-5.2.1-1 TYPICAL ROOM TEMPERATURE MECHANICAL PROPERTIES OF TITANIUM RIVET WIRE[11]

Alloy	F_{tu}, ksi	F_{ty}, ksi	Elong, %	RA %	F_{su} ksi
Ti-6Al-4V	145	128	14	46	90
Ti-6Al-4V(ELI)	136	118	13	47	87
Ti-4Al-3Mo-1V	130	118	15	57	83
Ti-3Al-2.5V	93	75	19	58	69
Ti-5Al-2.5Sn	127	106	14	41	83
CP-70A	100	71	--	--	75

to possible rapid attack when used with titanium in a corrosive environment. Galvanic corrosion can be reduced or eliminated by the use of copper-base, nickel-base, and stainless steel fasteners.[1] A286 rivets are also available and are being considered for use in titanium structures.

4-5.2.3 Bolts

There are two basic bolt types, one designed for shear loads, the other for tension loading.[1] Threaded fasteners made from Ti-6Al-4V and Ti-4Al-4Mn are currently stocked by a number of suppliers. Additional alloys, both titanium and higher strength alloys, are being studied for use in future fastener designs.

4-5.2.4 Other Fasteners

Other fasteners, such as lockbolts and hi-shear rivets made from Ti-6Al-4V and Ti-4Al-4Mn are also available and other titanium and high-strength alloys are being studied. A286 blind fasteners are available and the possibilities of titanium blind fasteners are being studied.

4-5.3 ASSEMBLY CONDITIONS AND TECHNIQUES

Assembly techniques for mechanically fastened titanium joints are similar to those used in aluminum and steel-alloy assembly. The only differences are in handling techniques. The titanium assembly should be kept clean and free of contaminants. This is absolutely necessary for critical applications. Drilling of holes in place requires disassembly and deburring of the pieces before a fastener is installed.

Proper alignment during assembly is most important, particularly for low-temperature applications. This is illustrated in Figure 4-5.3-1. The strength reduction shown in tests with a 3-degree-angle block is believed to indicate sensitivity to slight bending loads that might be imposed on the fasteners. This need for careful alignment emphasizes the importance of particular care in hole preparation. The alignment of the fastener can be no better than the alignment of the hole.

Assembly methods for common rivet- and bolt-type fasteners are discussed in the following paragraphs.

4-5.3.1 Rivets

There are many ways of riveting, all of them useful for particular applications.[1] Rivets may be installed either hot or cold. Cold riveting is used in most industrial operations because it is faster, more efficient, and eliminates potential thermal damage to the rivet and parts. A common method of setting rivets is with a rivet set and impact hammer. It is important with this method to use the proper size of rivet set and proper length of rivet, and to prevent battering of the parts being joined by set or back up.

Another method is squeeze riveting, in which a steady force is applied to both ends of the rivet. More precise control is possible with this method and battering of the parts being joined is avoided. Because the rivet is bulged out to form a cylinder larger in diameter than the hole, squeeze riveting is more tolerant of out-of-size holes and mismatching of holes than other methods of setting rivets.

Spin riveting may be used where a head is required and impact riveting is not desirable. A head is produced by the rotation of a tool against the rivet while it is held still. The clamping pressure of the rivet is controlled by the upsetting parameters. The rivet is set with no residual clamping pressure and the parts are left free to rotate around the rivet. This process provides neither the rigidity or hole filling of squeeze or impact driver rivets. Rivets so installed should therefore not be used at allowables determined for rivets driven by the more conventional methods unless the suitability of such use is verified by test.

4-5.3.2 Bolts

The strength of a bolted joint is greatly influenced by the amount of pretensioning in the bolt. Thus, it is necessary to produce the proper tension in the bolt during assembly This is done by applying the proper torque during assembly. Two methods of tightening bolts are:[1]

(1) Manual torque wrenching. A torque wrench has a dial that indicates the torque being applied. The nut is tightened to some preselected torque. Accurate but not fast.

(2) Pneumatic impact wrench. With this method, torque is controlled by air pressure or by a cutoff. When air-pressure control is used, the wrench stalls at the desired torque. The cutoff tool shuts off the air at the desired torque. This method is fast but not very accurate.

TABLE 4-5.2.2-1 YIELD AND ULTIMATE STRENGTH OF SOLID, 100-DEGREE-FLUSH-HEAD MONEL RIVETS IN MACHINE COUNTERSUNK TITANIUM ALLOYS[1]

Sheet Material	Commercially Pure Titanium				AMS 4901 Alloy(Ti-8Mn)		
Rivet Diameter, in.	1/8	5/32	3/16	1/4	1/8	5/32	3/16
Sheet Thickness, in.[b,c]							
			Yield Strength, lb[a]				
0.020	180	--	--	--	180	--	--
0.025	229	276	--	--	229	276	--
0.032	297	364	429	--	297	364	429
0.036	335	410	484	--	335	410	484
0.040	376	460	546	709	736	460	546
0.045	422	518	619	800	422	518	619
0.050	472	582	688	897	472	582	688
0.063	598	736	877	1,150	598	736	877
0.071	648	835	993	1,300	648	835	993
0.080	648	945	1,130	1,481	648	945	1,130
0.090	--	995	1,268	1,680	--	995	1,268
0.100	--	995	1,420	1,860	--	995	1,420
0.125	--	--	1,430	2,340	--	--	1,430
0.160	--	--	1,430	2,590	--	--	1,430
0.190	--	--	--	2,590	--	--	--
0.250	--	--	--	2,590	--	--	--
			Ultimate Strength, lb[a]				
0.020	307[d]	--	--	--	307[d]	--	--
0.025	386[d]	476[d]	--	--	386[d]	476[d]	--
0.032	492[d]	613[d]	732[d]	--	426	596[d]	732[d]
0.036	516[d]	686[d]	820[d]	--	451	627[d]	820[d]
0.040	531	765[d]	917[d]	1,216[d]	477	658	874[d]
0.045	555	795[d]	1,063[d]	1,363[d]	506	698	918
0.050	573	818	1,118[d]	1,512[d]	536	734	965
0.063	626	885	1,198	1,910[d]	617	83[illegible]	1,080
0.071	648	926	1,242	2,010[d]	648	894	1,152
0.080	648	971	1,302	2,090	648	961	1,243
0.090	--	995	1,360	2,185	--	995	1,330
0.100	--	995	1,421	2,260	--	995	1,421
0.125	--	--	1,430	2,460	--	--	1,430
0.160	--	--	1,430	2,590	--	--	1.430
0.190	--	--	--	2,590	--	--	--
0.250	--	--	--	2,590	--	--	--

(a) Higher allowables may be used if substantiated by test.
(b) Sheet gage is that of the countersunk sheet. Data are not applicable where the lower sheet is thinner than the upper sheet.
(c) In each strength column the sheet gage corresponding to the first strength value below the horizontal line in the column (——) represents the thinnest sheet gage of the top sheet in which the full depth of countersink can be made without entering the bottom sheet.
(d) For these values the yield load is less than two-thirds of the indicated ultimate load values.
Note: Values in this table are based on "good" manufacturing practice, any deviation from this will produce reduced values.

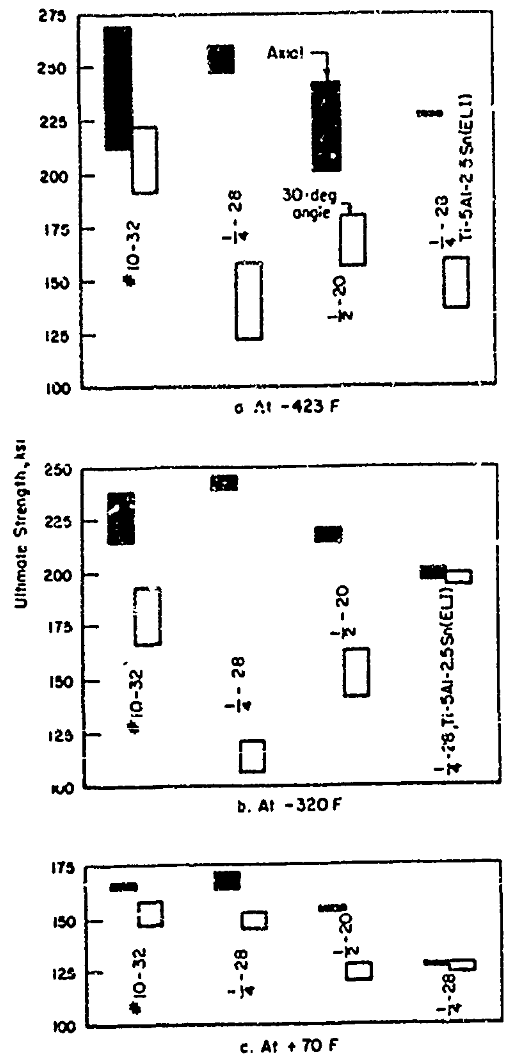

FIGURE 4-5.3-1. COMPARISON OF ULTIMATE STRENGTH WITH AXIAL AND 3-DEGREE-ANGLE-BLOCK LOADING (REF. 22)

Ti-8Al-1Mo-1V bolts with A-286 nuts.

With either of these two methods, accuracy can be assured to very close tolerance by measuring the bolt length with a micrometer both before and after assembly.

About 90 percent of the torque applied during tightening is used to overcome friction. The balance produces tension in the bolt. The torque required to overcome friction may be even higher than this with titanium bolts. The induced load obtained in titanium bolts at several levels of torque is shown in Figure 4-5.3.2-1. However, for critical applications, actual torque values should be arrived at by experiment.

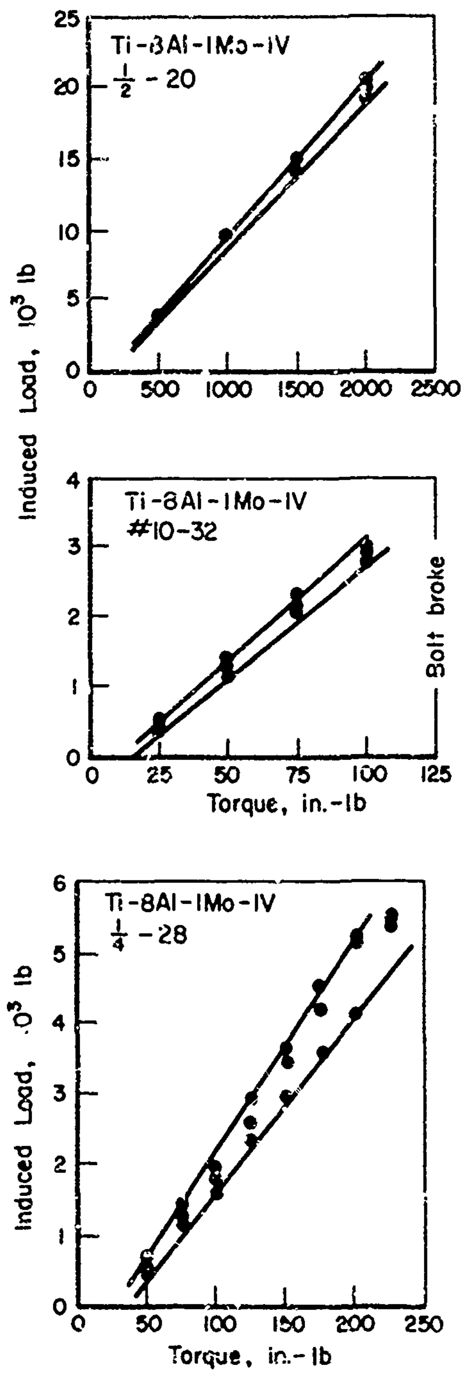

FIGURE 4-5.3.2-1. TORQUE VERSUS INDUCED LOAD FOR TITANIUM TENSION FASTENERS (REF 13)

All data obtained from A-286 nuts. Bolt yield strength, 136 to 144 ksi, bolt ultimate strength, 154 to 171 ksi. Data from three consecutive tests, induced load generally higher on last test

4-5.4 REFERENCES

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SECTION 5
Mechanical and Physical Properties

Mechanical and Physical Properties Con't.

5-0 General Remarks

5-0.0 INTRODUCTION

The information on mechanical and physical properties presented in this section is based on data acquisition and analysis procedures universally accepted by today's aerospace industry. With MIL-HDBK-5 and current applicable military specifications as the starting point, data were collected on commercially pure titanium and eight titanium alloys: Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-13V-11Cr-3Al, Ti-4Al-3Mo-1V, Ti-679, and Ti-6Al-2Sn-4Zr-2Mo. Information sources have been carefully checked to assure that there is no duplication of data.

Some strength information (noted as tentative) has been presented on the basis of small quantities of data. This procedure is justified by the current necessity for preliminary design-strength values. It is recognized that these values will change as more test information becomes available.

The material-properties information presented herein reflects the characteristics of titanium alloys as currently produced. Process improvements subsequently incorporated will modify these data.

In this handbook, fatigue-crack propagation and residual strength (or fracture toughness) are considered. Both material behaviors are topics new to handbook presentation and have not reached the status of design allowables. Their treatment in this handbook is as indicative information, which the designer may use at his discretion. Although qualitative studies have shown that an aqueous environment is detrimental to cracked material, quantitative engineering data for titanium alloys in this condition are not yet available. Mechanical fastening is also presented in the introductory section because the information available is too limited to make a design presentation. Criteria guidelines are discussed, followed by a limited display of exposure and fatigue data. This material is presented as indicative information only.

It should be noted that Section 1 discusses the detailed metallurgical aspects of the alloys whose design properties are presented here. Heat treatments, stabilization, and other considerations are brought out there. In order to give the designer the fullest appreciation of the subtleties and peculiarities of titanium technology, these sections should be considered together.

Data references are listed in Section 5-20. Superscripts following figure titles cite applicable references. Uncited titles imply information derived from MIL-HDBK-5.

5-0.1 DIGITAL IDENTIFICATION

Within Section 5, a three-digit code is utilized to identify the subsections. After the initial dash, the first digit identifies the alloy: 1 for commercially pure titanium through 9 for titanium alloy Ti-6Al-2Sn-4Zr-2Mo. The second digit denotes room-temperature allowables, environmental effects, or thermophysical properties. The third digit denotes subcategories to these. Thus, for titanium alloy Ti-8Al-1Mo-1V, the following identification applies:

5-3	Alloy
5-3.1	Room-temperature allowables
5-3.2	Environmental effects for the first heat treated condition
5-3.2.1	Elevated-temperature effects
5-3.2.2	Effect of exposure
5-3.2.3	Stress-strain and tangent modulus curves
5-3.2.4	Creep data
5-3.2.5	Fatigue behavior
5-3.2.6	Residual-strength data
5-3.3	Environmental effects for the second heat-treated condition
5-3.3.1	Elevated-temperature effects
5-3.3.2	Etc.
....	....
5-3.4	Thermophysical properties

Subsequent dash numbers denote tables and figures in the respective categories.

It should be noted that the existence of identification for all subsections does not imply that data are available in that area. Rather, it indicates that accommodation has been made for the data when they become available. The table of contents catalogs subsections in which information is presented. Data voids may occur for several reasons: testing not yet performed in depth; production changes have voided existing data; or proprietary, economic, or security factors prohibit the source from releasing data.

5-0.2 MECHANICAL PROPERTIES

5-0.2.1 Room-Temperature Design Mechanical Properties

In the material sections to follow, tabulations of room-temperature mechanical properties according to product, heat treatment, and gage range are made for tension, compression, shear, bearing, elongation, and modulus properties. In most cases, values in the room-temperature-properties tables apply to both longitudinal and transverse properties. Where differences in strength occur, two values are listed (L and T).

In accordance with the Guidelines of MIL-HDBK-5, tension-yield and ultimate-strength data were analyzed and presented on one of three bases: Design Allowable A Basis, Design Allowable B Basis, or Specification S Basis. Specifically, these are defined as follows:

A Basis. — The mechanical-property value indicated is the value above which at least 99 percent of the population of values is expected to fall, with a confidence of 95 percent.

B Basis. -- The mechanical-property value indicated is the value above which at least 90 percent of the population of values is expected to fall, with a confidence of 95 percent.

S Basis. -- The mechanical-property value indicated is the specified minimum value of the governing Military Specification or SAE Aerospace Material Specification for this material. The statistical assurance associated with this value is not known; however, they are considered to represent present production capability.

For well-established alloys, A values and S values are identical. For newer alloys, where processing is subject to change, the possibility exists for differences between A and S values at any one time.

Compression, shear, and bearing properties are derived values whose room-temperature values are established through their relationship to room-temperature tension-yield and ultimate-strength values. This is accomplished by pairing individual ultimate-strength measurements with ultimate tensile-strength measurements, or yield-strength with tensile yield-strength, determining the mean ratio of these pairs of measurements, with a probability of 95 percent, and multiplying the directly calculated A or B value or the S value for tension ultimate or yield strength by this factor. Ten pairs of measurements have been considered a minimum for establishing a derived allowable where adequate background information is available. For completeness of presentation, where less than ten sample tests were available, tentative values (enclosed in parentheses) are tabulated for compression, shear, and bearing allowables. These values are based on best engineering judgment of data available. In areas where no test data were available, they have been developed from ratios applicable to a similar titanium alloy. The tentative values are included for indicative purposes only and should be used conservatively in design. Elongations are tabulated on an S basis.

For convenience to the user of this document, portions of the room-temperature property tables that have not been approved by, or are in conflict with, MIL-HDBK-5A tables are denoted by shading. In some cases, shaded mechanical-property values represent changes that may be expected to be approved for MIL-HDBK-5A in the near future, such as those representing changes currently being made in procurement specification requirements. Similarly, figures that either differ from those in MIL-HDBK-5A, or are considered tentative, are denoted by shading of the captions beneath the figures. In other cases, the shaded values represent tentative values based on limited data; these include both suggested specification values for F_{tu}, F_{ty}, and e, and tentative derived values (see above), both types of which are enclosed in parentheses.

5-0.2.2 Environmental Effects

For each heat-treatment condition for which data are available, design allowables can be computed based upon the room-temperature tables and the graphs presented in the Environmental Effects sections. The graphs may indicate how temperature affects strength or how exposure at temperature affects room-temperature strength. These graphs are plotted as percent-strength versus temperature (either test temperature or exposure temperature). Percent-strength values obtained from these graphs when multiplied by the appropriate room-temperature property (considering product form, gage and heat treatment) yield the required design-strength value.

In the Environmental Effects sections, tensile and compressive stress-strain diagrams and tangent-modulus curves are plotted for discrete temperatures. Creep data are presented as stress-versus-time plots for various creep-strain criteria. Depending upon the quantity and range of data, fatigue information is plotted as S-N curves or as constant-life diagrams. The presentations here are made in accordance with the procedural Guidelines of MIL-HDBK-5.

Residual-strength data are presented here in a limited form. Since there is no established format for the display of this information, the attempt has been made to display these data in the simplest and most useful manner for the designer. Further discussion of this information follows in Section 5-0.4.

5-0.3 THERMOPHYSICAL PROPERTIES

Specific heat, thermal conductivity, linear expansion, and electrical resistivity are presented graphically versus temperature in each alloy section.

5-0.4 FATIGUE AND FRACTURE TOUGHNESS IN DESIGN

With the advent of fail-safe and safe-life design concepts, it was recognized that crack formation in structural elements is due to inherent metallurgical

characteristics as well as to mechanical defects. As a result, considerable research has been devoted to studies of crack formation, propagation, and final fracturing. Several complex theories have evolved and have received some experimental substantiation; however, the extensive data required to perform statistical analyses and to set design guidelines are not available.

To emphasize the fact that for titanium, as well as for all metals, data pertinent to these topics have not yet reached the status of design allowables, certain of the information is presented in this introductory section. It is again noted that the effects of an aqueous environment are not included.

5-0.4.1 Fatigue-Crack Propagation

The growth rate of cracks initiated by metallurgical or mechanical flaws defines the effective service life of any given structural element. To maintain structural integrity and to define inspection requirements, crack growth must be known from the threshold of its detection until it reaches the point of rapid fracturing.

Extensive testing has been accomplished on a wide variety of specimens under many cyclic loading conditions. Rather than presenting a complete bibliography of data, the attempt has been made to select the data to illustrate important relationships. In the figures that follow, the designer should note the influence of stress amplitude, stress ratio, mean stress, and the geometric parameters of thickness, size, and curvature.

Crack-propagation data for 8-inch-wide, duplex-annealed Ti-8Al-1Mo-1V alloy sheet is presented in Figures 5-0.4.1-1 through 5-0.4.1-4 for various temperatures and stress ratios, R. The first two figures are for thin sheet, while the latter are for thick sheet. These particular data were obtained at a mean stress of 25 ksi. It may be noted that specimen life increases with a decrease in stress amplitude. It should also be noted that no consistent temperature effects are displayed. Figure 5-0.4.1-5 presents comparable room-temperature crack propagation for a 0.200-inch-thick specimen from another source. Here the expected effect of stress ratio, R, also is displayed.

For comparison of geometric effects, data for specimens for 24-inch width and greater are presented in the remaining figures. Room-temperature crack-propagation data for duplex-annealed Ti-8Al-1Mo-1V alloy thin sheets at different stress ratios and maximum stresses are presented in Figures 5-0.4.1-6 through 5-0.4.1-9. Comparable thick-sheet data are presented in Figure 5-0.4.1-10 for a maximum stress of 25 ksi. Mill-annealed Ti-6Al-4V alloy thin-sheet data are presented in Figures 5-0.4.1-11 and 5-0.4.1-12. In all of these figures, an increase of specimen life with increasing R is shown as expected.

Data for 36-inch-wide, stiffened and unstiffened, duplex-annealed Ti-8Al-1Mo-1V alloy thin sheets are presented in Figure 5-0.4.1-13. Although transverse stiffening does not affect the crack growth rate up to about 10,000 cycles, it apparently lengthens the cyclic life of the specimen. Propagation data for a pressure-cycled, unstiffened titanium cylinder are displayed in Figure 5-0.4.1-14. The cyclic life of the cylinder is seen to be extremely short in comparision with the flat specimens.

Growth-rate comparison for a 4-inch crack in the large specimens is displayed in Figure 5-0.4.1-15. Within the Ti-8Al-1Mo-1V alloy sheets, growth rate increases with thickness. The striking spread of growth-rate data over four log cycles brings out the strong implication of geometry. Both size and curvature are important parameters in this area.

From 1965 to the present time, rather extensive research has been conducted to determine the susceptibility of titanium alloys to reduced fracture strength in the presence of various liquids. In many cases, the titanium alloy under study is not intended for use in the specific environments, but rather the environmental studies are intended to define the criticality of the problem. Much of this activity resulted from the findings of Dr. B. F. Brown at the Naval Research Laboratory. He found that Ti-8Al-1Mo-1V and Ti-7Al-2Cb-1Ta alloys were seriously affected when tested in the presence of distilled water or a 3.5% NaCl solution. After these findings, a flourish of activity resulted on programs related to the structural application of titanium alloys, particularly in applications where reduced fracture strength in the presence of some liquids is of importance.

In addition to the fact that the fracture strength of titanium alloys may be affected adversely by the presence of a liquid environment, the fatigue-crack-propagation behavior may be affected adversely. Results pertaining to fatigue-crack-propagation behavior are presented and briefly discussed in the following paragraphs.

Curves of crack length versus number of cycles are presented in Figures 5-0.4.1-16 to 5-0.4.1-30 for the Ti-6Al-4V alloy and in Figures 5-0.4.1-31 to 5-0.4.1-35 for the Ti-4Al-3Mo-1V alloy. Various heat treatments and thicknesses were studied, and the results are shown in these figures. In general, the figures show crack length versus number of cycles for the indicated R values and three environmental conditions; namely, room air, distilled water, and 3.5% NaCl solution.

These results are summarized in Figure 5-0.4.1-36 for the Ti-6Al-4V alloy and in Figure 5-0.4.1-37 for the Ti-4Al-3Mo-1V alloy. Figure 5-0.4.1-36 demonstrates rather clearly the influence of 3.5% NaCl solution, distilled water, and room air on the fatigue-crack-propagation behavior of four heat treatments of Ti-6Al-4V. The influence of thickness is also indicated on the figure. The results summarized in the latter two figures were obtained on 12 x 36-inch center-cracked panels tested at two different R values, using a mean stress of 25 ksi. The ordinate in Figures 5-0.4.1-36 and 5-0.4.1-37 represents the number of cycles to grow a crack from a length of 2.0 inches to 3.5 inches. From these two figures, it is seen that both the distilled water and 3.5% NaCl solution accelerate crack growth. A greater effect of environment is observed for an R value of 0.67. Increasing the thickness tends to accelerate crack growth in both the air and aqueous environments.

From the results presented in the latter two figures, it is possible to conclude that the environmental crack resistance of the Ti-6Al-4V alloy, for the four heat treating conditions studied, in order of decreasing resistance, is:

1) Beta STA - 1250*
2) Duplex annealed
3) Mill annealed
4) Beta STA - 1000

For the Ti-4Al-3Mo-1V alloy, the environmental crack growth resistance is about the same in both heat treatments. They, in turn, are about equal to the Ti-6Al-4V duplex-annealed material in their environmental resistance to crack growth.

Figures 5-0.4.1-38 and 5-0.4.1-39 demonstrate the resistance of Ti-8Al-1Mo-1V sheet and Ti-6Al-4V sheet, respectively, to environmental flaw growth. These data were obtained on 8 x 24-inch center-cracked panels tested at an R value of 0.1 and a mean stress value of 25 ksi. In both cases, the salt water results in serious degradation of the fatigue-crack-growth resistance.

Additional insight into the deleterious effects of fatigue-crack-growth in the presence of an aqueous environment can be obtained from reference (75). In this case, fatigue-crack-propagation tests were conducted on Ti-8Al-1Mo-1V (duplex annealed) to ascertain the difference in crack-growth rate between testing in air, seawater, and alternate exposure to elevated temperature and seawater. Testing was done on 8 x 24-inch center-cracked panels at a mean stress level of 25 ksi and various alternating stress levels. The panel thickness in all cases was 0.050 inch. The results are shown in Figure 5-0.4.1-40. Generally, the fatigue cracks propagated more rapidly under the combined aqueous and thermal soak conditions than in air. The test at an S_o value of 40 ksi (S_o is the maximum load divided by the initial net section area) shows that the results for heat soaking plus immersion and immersion only are nearly identical. This lead to the conclusion that most of the degradation in crack-propagation rate for the heat soaking plus immersion cycle is due to the effect of the aqueous environment.

*These heat treatments are described in Section 5-4.0.

The preceding results indicate that the presence of an aqueous environment leads to a serious degradation of fatigue-crack-growth resistance for the Ti-6Al-4V, Ti-8Al-1Mo-1V, and Ti-4Al-3Mo-1V alloys.

A more general analysis of these data is beyond the scope of this handbook. More than a dozen formulations are in current use to correlate these data and, since individual design organizations have their own preferences for analysis procedures, these choices are left to them. For further information, the designer is referred to the References, 5-20, at the end of this section.

5-0.4.2 Fracture Toughness and Residual Strength

The nominal design of tension structure is based on the premise that the integrity of a component is not compromised until its critical section reaches the material yield strength, and that the material ultimate strength in its critical section can be realized before fracture occurs. Factors of safety are then utilized to account for irregularities in loading and material behavior. However, the occurrence of flaws, such as cracks, weld defects, and metallurgical inclusions, can cause structural failure at loadings well below those of the nominal design. While unintentional in design, these flaws are an unavoidable circumstance of fabrication or service.

Several procedures have evolved to describe material behavior in the presence of flaws. Those techniques that are stress related have proven most amenable to design application. The maximum gross stress that a structural material can sustain in the presence of a designated flaw is termed its residual strength. The material parameter that relates this gross stress and flaw size is termed fracture toughness.

From Griffith-Irwin theory, the field of fracture mechanics has developed. Here, a stress-intensity factor, K, is utilized to relate residual strength and crack length. The critical value of K at the onset of rapid fracture, or the fracture toughness, is identified as K_{Ic} or K_c under conditions of plane strain or plane stress, respectively. From an engineering perspective, two other procedures have evolved. Empirical

curve-fitting procedures have been suggested by Bockrath and Jackson. Bockrath relates the net-to-ultimate stress ratio to a power of the crack length; Jackson uses the gross-to-yield stress ratio. An "effective width" method has been used by Crichlow, Denke, and Kuhn to define a hypothetical plastic zone adjacent to the crack or flaw. A general development of these approaches is beyond the scope of this handbook, each method has its limitations and regimes of applications.

In the evolution of the SST program, the fracture resistance of titanium alloys in the presence of flaws has been evaluated primarily in two manners. For relatively thick section products, such as plate and forgings, the concepts of plane-strain fracture-toughness testing[79,80] have been utilized to define a critical plane-strain stress-intensity factor (or fracture toughness), K_{Ic}. For relatively thin-section products, such as sheet and strip, the center-cracked sheet tear test has been utilized to relate the residual gross stress at fracture to the central crack length.

While the ASTM Committee E-24 is in process of standardizing test methods, they are not firmly established. As a result, only a limited quantity of consistent data are available. This information is included in this introductory section as indicative and qualitative information only. It should not be considered as typical, average, or minimum for design until further substantiated.

For the quasi-plane-strain conditions of thick-section material, the critical plane-strain stress-intensity factor is defined by fracture mechanics as

$$K_{Ic} = F_g(\pi a)^{1/2} \cdot Y, \qquad (1)$$

where

F_g = gross stress at fracture, psi
a = flaw size, inches (generally a crack length)
Y = nondimensional compliance factor dependent on flaw and specimen geometry.

To demonstrate the deleterious effect of environment, sustained-load fracture tests have been conducted in salt water. Although aircraft do not operate in salt water and these data may be too severe for design criteria, the hostile influence of a salt water environment must be recognized. These data serve primarily as precautionary indicators. Delayed fracture characteristics in salt water are shown by the environmental crack-growth-resistance factor, K_{Ii}. This is determined in the same manner as Equation (1), with F_g being the gross stress at fracture after some period of exposure.

The influence of metallurgical stability on fracture characteristics has been studied. Room-temperature values of K_{Ic} and K_{Ii} have been determined after extended exposure times at various anticipated service temperatures.

A summary of plane-strain fracture-toughness values for material and processes selected by Boeing and Lockheed and presented in Table 5-0.4.2-1 and Figures 5-0.4.2-1 and -2. Tensile-ultimate and yield-strength control test values are included for comparative purposes. Note that Boeing's environmental data, K_{Ii} values, are based on 6-hour exposures, Lockheed's are based on 3-hour exposures.

In the thin-section titanium-alloy product, the residual strength is that maximum gross stress that a center-cracked sheet specimen will sustain. Lockheed reports these data as a gross section stress, F_g, and an initial crack length in a given size panel. Boeing performs similar tests but summarizes the data as a critical plane-stress stress-intensity factor, K_c. While this value is larger than K_{Ic} because of plasticity effects, it has a similar analytical expression. For the case of a central, through-the-thickness crack, Boeing uses the compliance factor,

$$Y = \left[\frac{W}{\pi a} \tan \frac{\pi a}{W}\right]^{1/2},$$

such that

$$K_c = F_g \left(W \tan \frac{\pi a}{W}\right)^{1/2} \qquad (2)$$

where

W = panel width, inches

a = half-crack length, inches.

Environmental residual-strength data are presented on a similar basis. The gross fracture stress in salt water is denoted F_{gsw} and replaces F_g in the above expression.

A summary of residual-strength data for material and processes selected by Boeing and Lockheed are presented in Table 5-0.4.2-2 and in Figures 5-0.4.2-3 and 5-0.4.2-4. Tensile-strength values from control tests have been included for comparision. For the salt water environment, Boeing again used a 6-hour sustained load, whereas Lockheed again used a 3-hour sustained load.

Where residual-strength data over a wider range of crack lengths are available, graphical displays of the data are presented in the alloy sections to follow. To date, a wide variety of specimen configurations have been subjected to residual-strength tests. However, the variation of fundamental parameters in a given configuration has been too limited to allow the overlap of data necessary to correlate tests on a general scale. For this reason, residual-strength data are presented by specific types of specimens. Gross stress is plotted versus initial or critical crack length, where it is to be noted that gross stress equals

ultimate strength at zero crack length, and gross stress is zero when the crack length equals the specimen widths. Where the critical crack length was not determined, the initial fatigue crack length was used. From the gross stress, crack length, and other fundamental parameters identifying the specimen type, the knowledgeable designer may calculate the fracture toughness indices With some engineering judgment, he may also estimate the tolerable crack length in a given specimen.

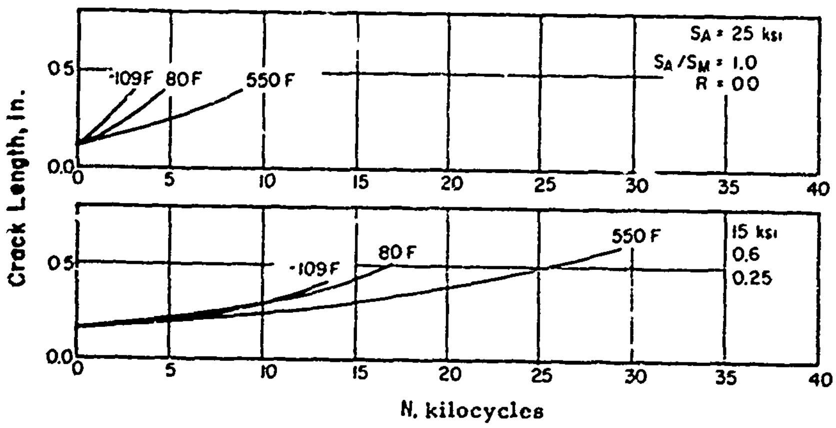

FIGURE 5-0.4.1-1. CRACK-PROPAGATION DATA FOR 8-INCH-WIDE DUPLEX ANNEALED Ti-8Al-1Mo-1V ALLOY OF 0.050-INCH NOMINAL THICKNESS AT 25-KSI MEAN STRESS, LONGITUDINAL GRAIN DIRECTION(45)

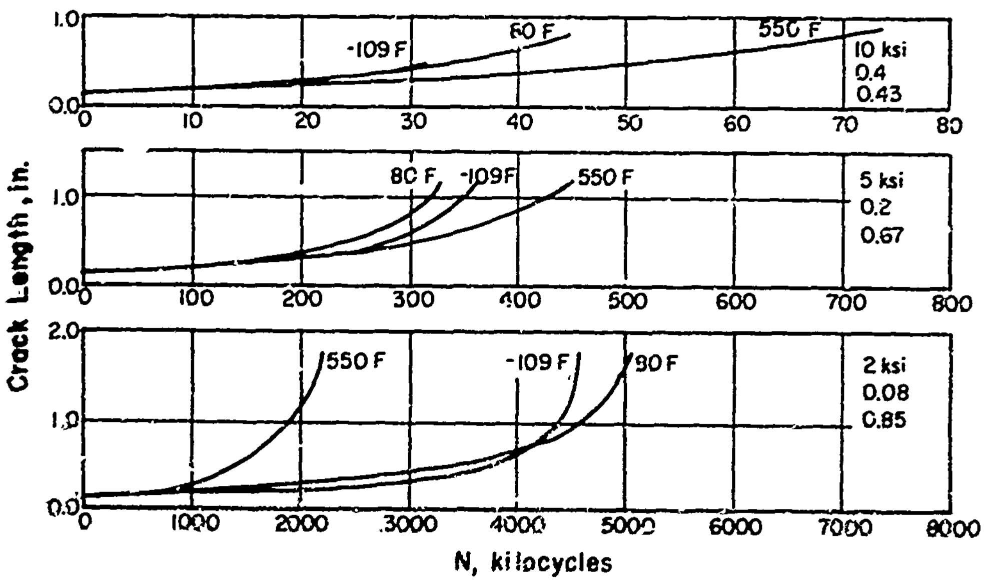

FIGURE 5-0.4.1-2. CRACK-PROPAGATION DATA FOR 8-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY OF 0.050-INCH NOMINAL THICKNESS AT 25-KSI MEAN STRESS, LONGITUDINAL GRAIN DIRECTION(45)

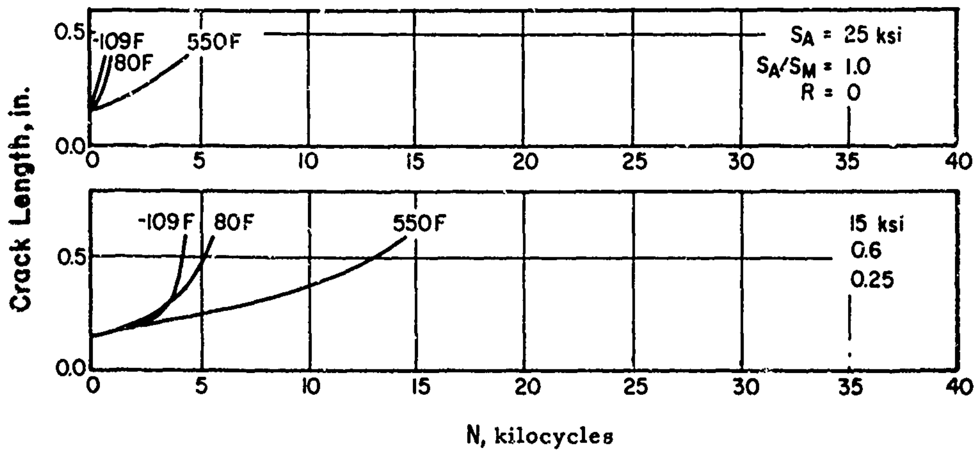

FIGURE 5-0.4.1-3. CRACK-PROPAGATION DATA FOR 8-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY OF 0.250-INCH NOMINAL THICKNESS AT 25-KSI MEAN STRESS, LONGITUDINAL GRAIN DIRECTION[45]

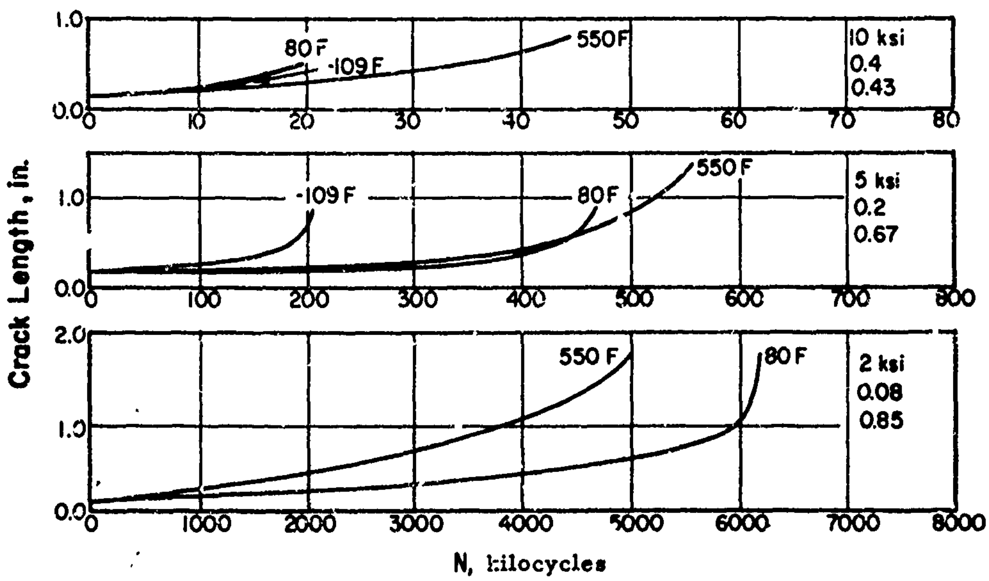

FIGURE 5-0.4.1-4. CRACK-PROPAGATION DATA FOR 8-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY OF 0.250-INCH NOMINAL THICKNESS AT 25-KSI MEAN STRESS, LONGITUDINAL GRAIN DIRECTION[45]

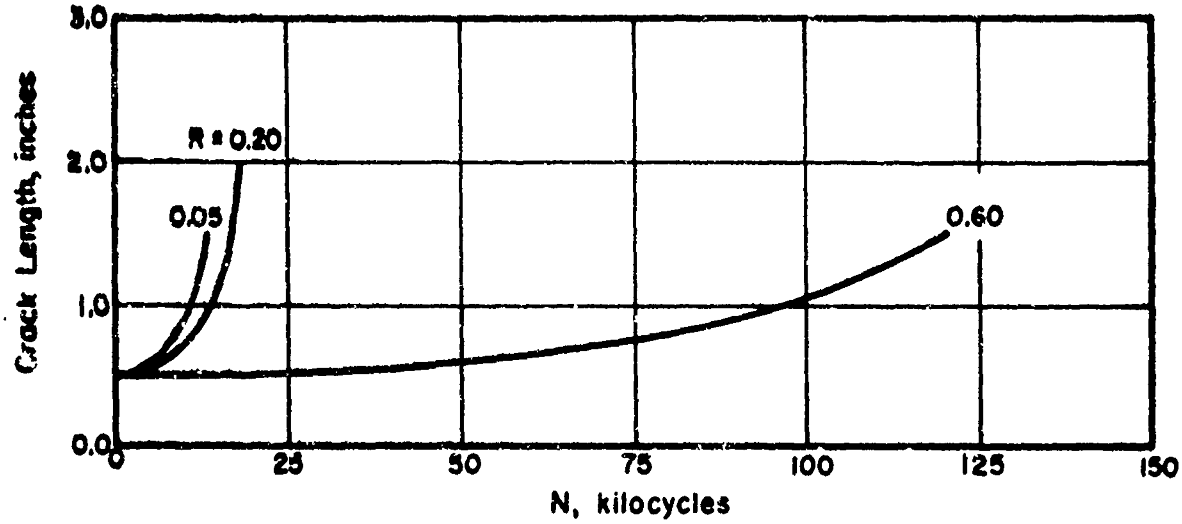

FIGURE 5-0.4.1-5. CRACK-PROPAGATION AT ROOM TEMPERATURE FOR 8-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V OF 0.200-INCH NOMINAL THICKNESS, CYCLED AT A MAXIMUM STRESS OF 25-KSI, TRANSVERSE GRAIN DIRECTION, 120 CPM(37)

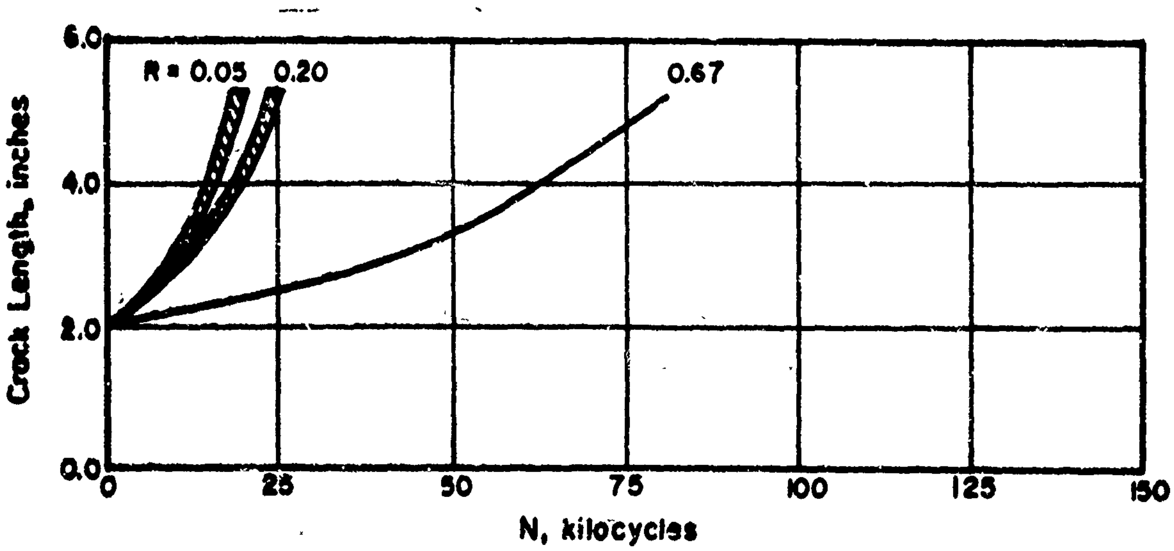

FIGURE 5-0.4.1-6. CRACK-PROPAGATION DATA AT ROOM TEMPERATURE FOR 24-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY SHEE OF 0.050-INCH NOMINAL THICKNESS CYCLED AT A MAXIMUM STRESS OF 25-KSI, LONGITUDINAL GRAIN DIRECTION, 120 CPM(37)

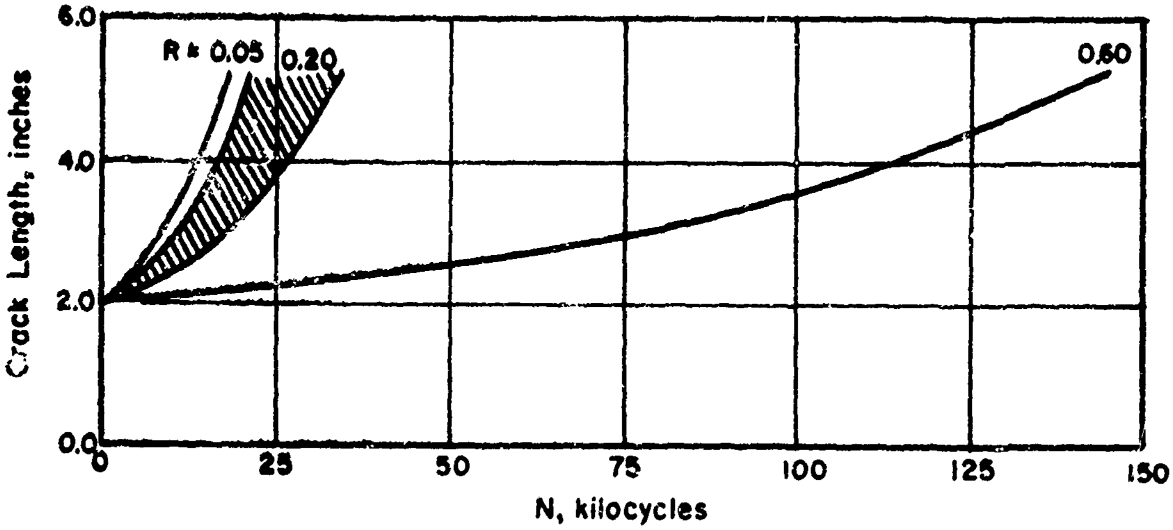

FIGURE 5-0.4.1-7. CRACK-PROPAGATION DATA AT ROOM TEMPERATURE FOR 24-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY SHEET OF 0.050-INCH NOMINAL THICKNESS CYCLED AT A MAXIMUM STRESS OF 25-KSI, TRANSVERSE GRAIN DIRECTION, 120 CPM(37)

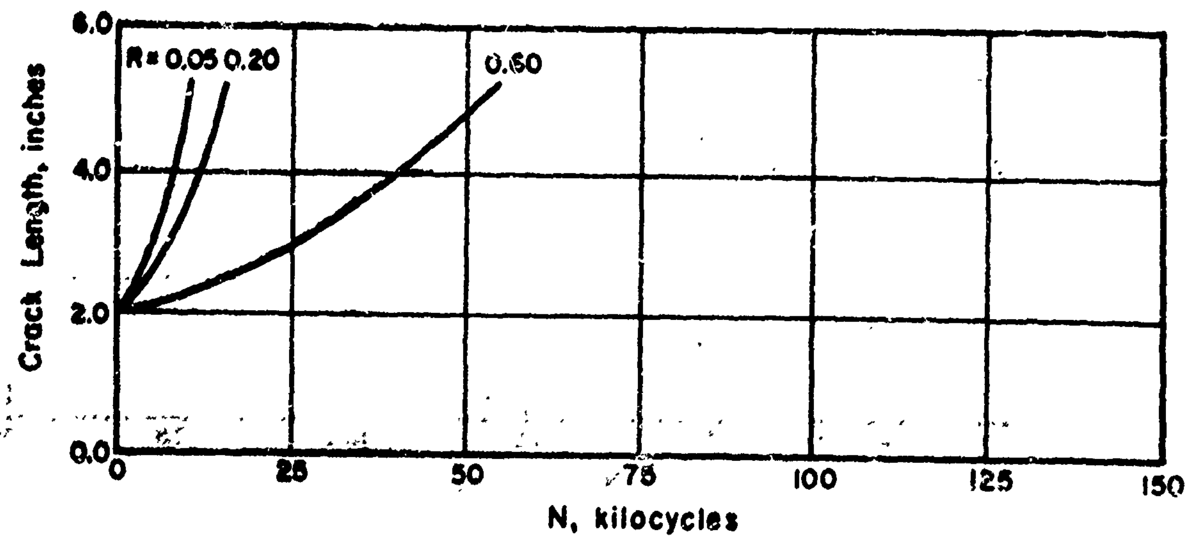

FIGURE 5-0.4.1-8. CRACK-PROPAGATION DATA AT ROOM TEMPERATURE FOR 24-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY SHEET OF 0.050-INCH NOMINAL THICKNESS CYCLED AT A MAXIMUM STRESS OF 30-KSI, LONGITUDINAL GRAIN DIRECTION, 120 CPM(37)

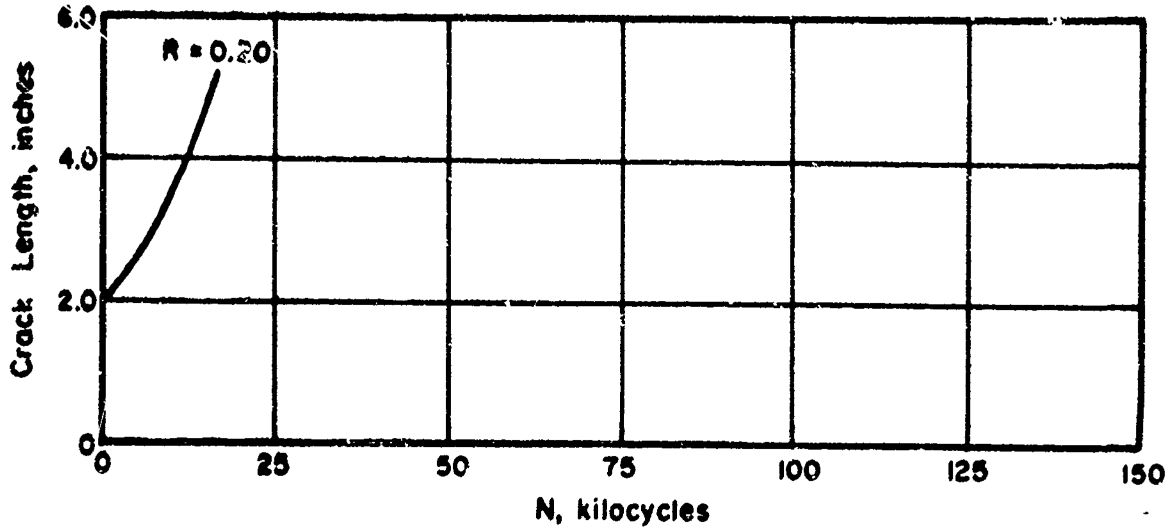

FIGURE 5-0.4.1-9. CRACK-PROPAGATION DATA AT ROOM TEMPERATURE FOR 24-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY SHEET OF 0.050-INCH NOMINAL THICKNESS CYCLED AT A MAXIMUM STRESS OF 30-KSI, TRANSVERSE GRAIN DIRECTION, 120 CPM(37)

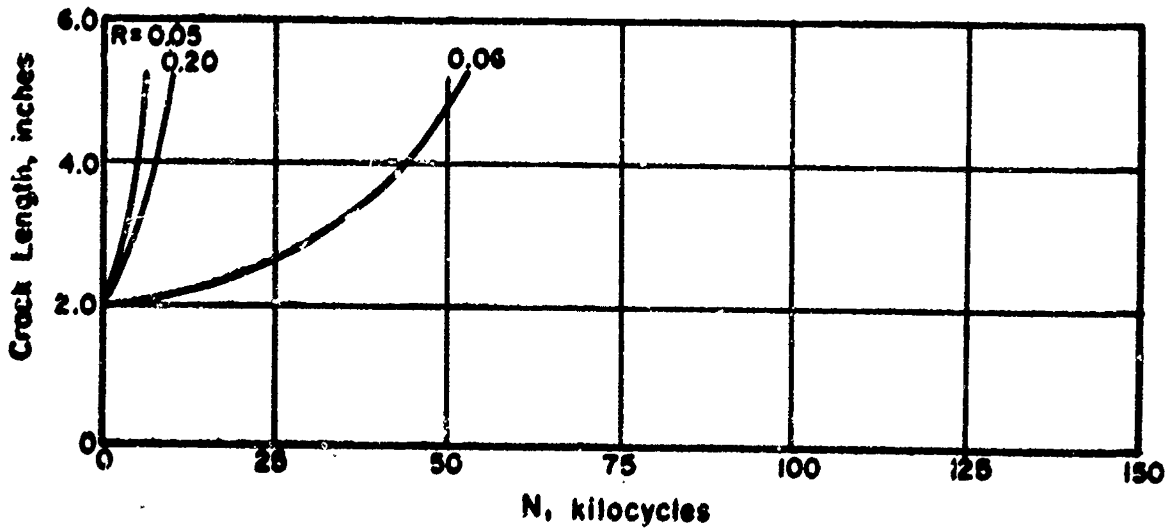

FIGURE 5-0.4.1-10. CRACK-PROPAGATION DATA AT ROOM TEMPERATURE FOR 24-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY SHEET OF 0.200-INCH NOMINAL THICKNESS CYCLES AT A MAXIMUM STRESS OF 25-KSI, LONGITUDINAL GRAIN DIRECTION, 120 CPM(37)

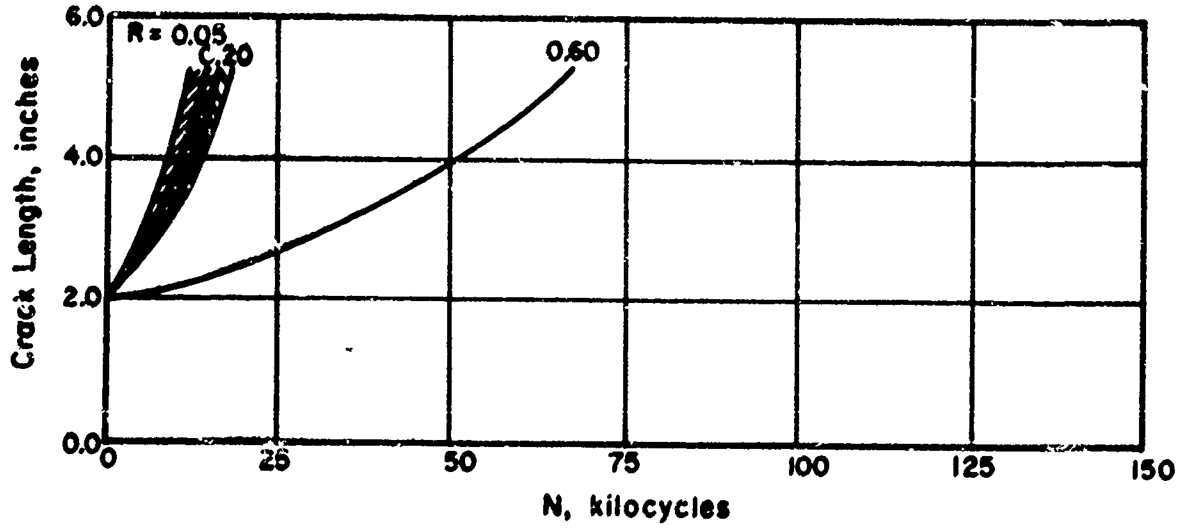

FIGURE 5-0.4.1-11. CRACK-PROPAGATION DATA AT ROOM TEMPERATURE FOR 24-INCH-WIDE, MILL-ANNEALED, Ti-6Al-4V ALLOY SHEET OF 0.050-INCH NOMINAL THICKNESS CYCLED AT A MAXIMUM STRESS OF 25-KSI, LONGITUDINAL GRAIN DIRECTION, 120 CPM[37]

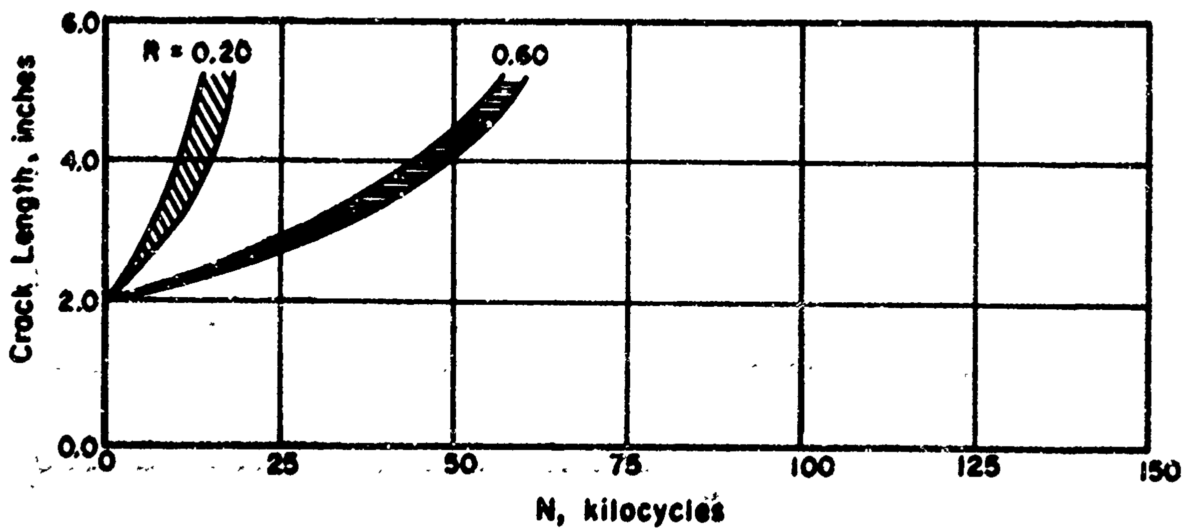

FIGURE 5-0.4.1-12. CRACK-PROPAGATION DATA AT ROOM TEMPERATURE FOR 24-INCH-WIDE, MILL-ANNEALED, Ti-6Al-4V ALLOY SHEET OF 0.050-INCH NOMINAL THICKNESS CYCLED AT A MAXIMUM STRESS OF 25-KSI, TRANSVERSE GRAIN DIRECTION, 120 CPM[37]

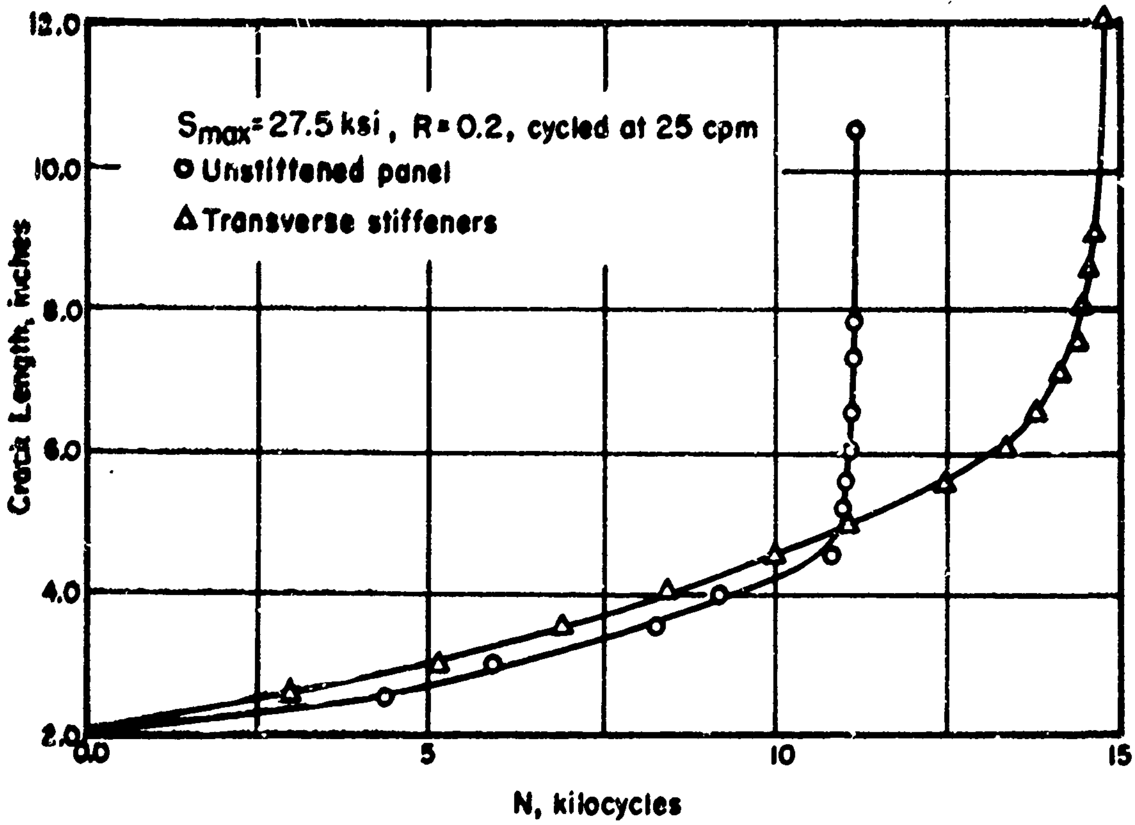

FIGURE 5-0.4.1-13. CRACK-PROPAGATION DATA FOR 36-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY SHEET OF 0.032-INCH NOMINAL THICKNESS(33)

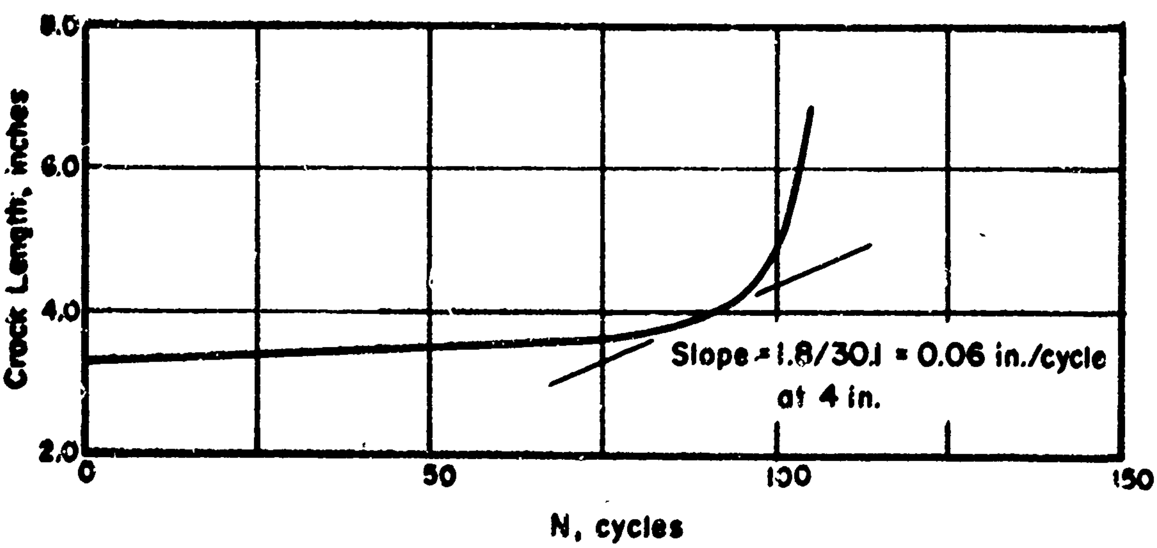

FIGURE 5-0.4.1-14. CRACK-PROPAGATION DATA FOR DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY CYLINDER (RADIUS = 15 INCHES, LENGTH = 60 INCHES) OF 0.050-INCH NOMINAL THICKNESS AT A MAXIMUM CYCLIC STRESS OF 25-KSI WITH R = 0(33)

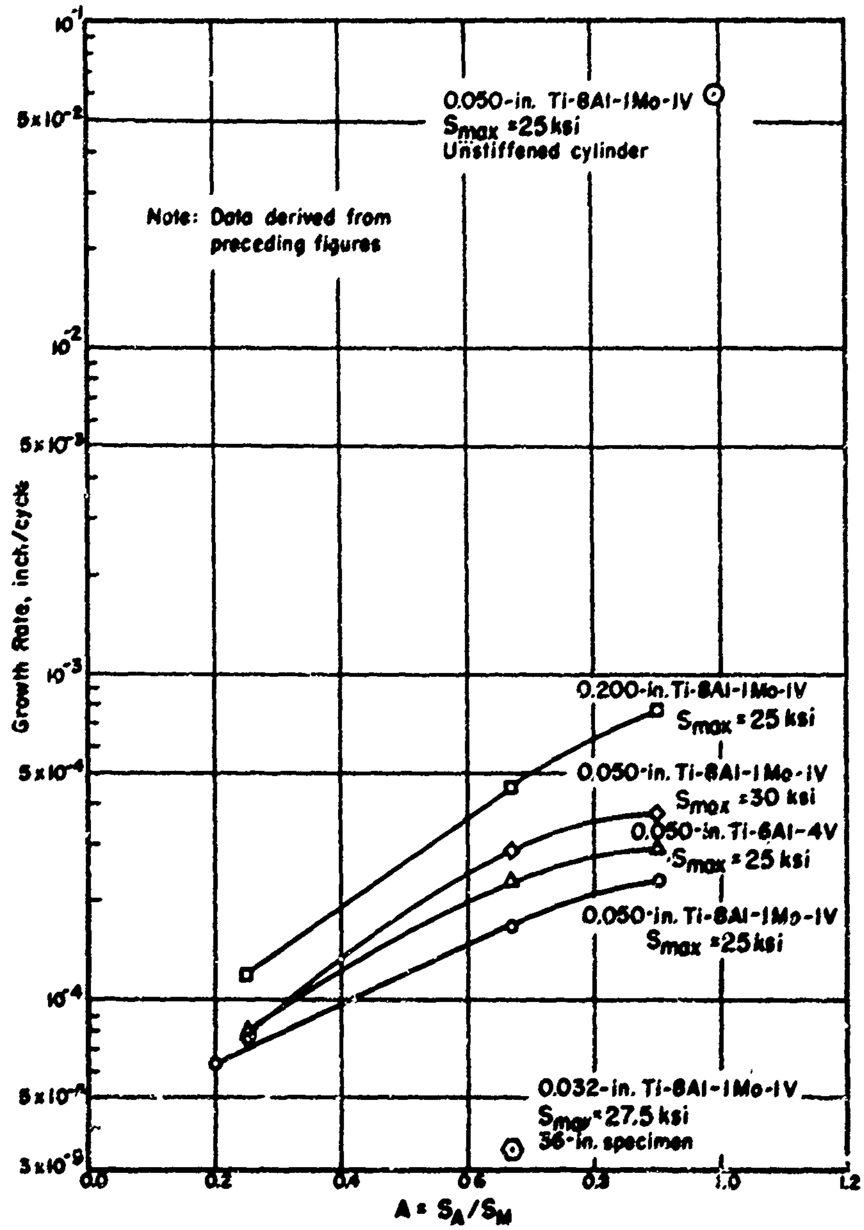

FIGURE 5-0.4.1-15. CRACK GROWTH RATE VERSUS AMPLITUDE-MEAN STRESS RATIO FOR VARIOUS LARGE SPECIMENS AT A 4-INCH CRACK LENGTH

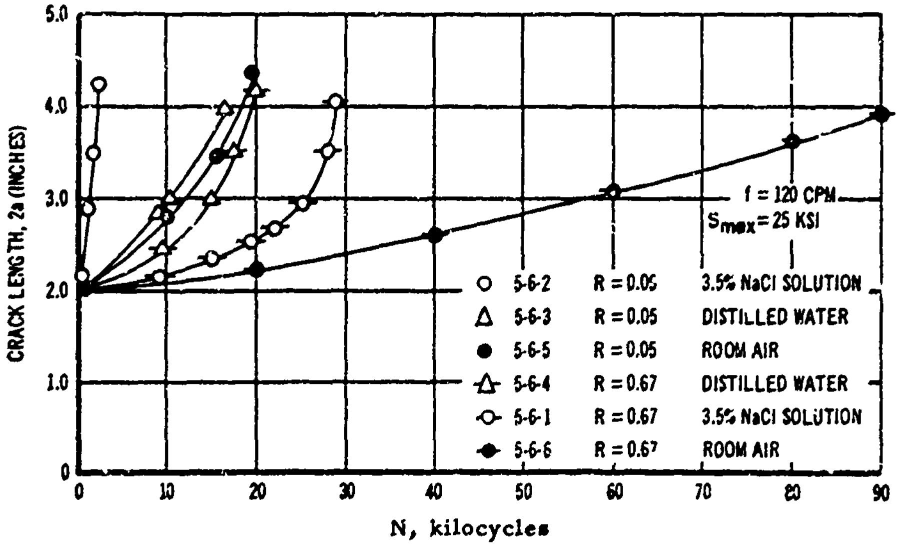

FIGURE 5-0.4.1-16. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V,BETA-STA-1250, 0.050-INCH-THICK (CHEM MILLED FROM 0.063 Inch) (73)

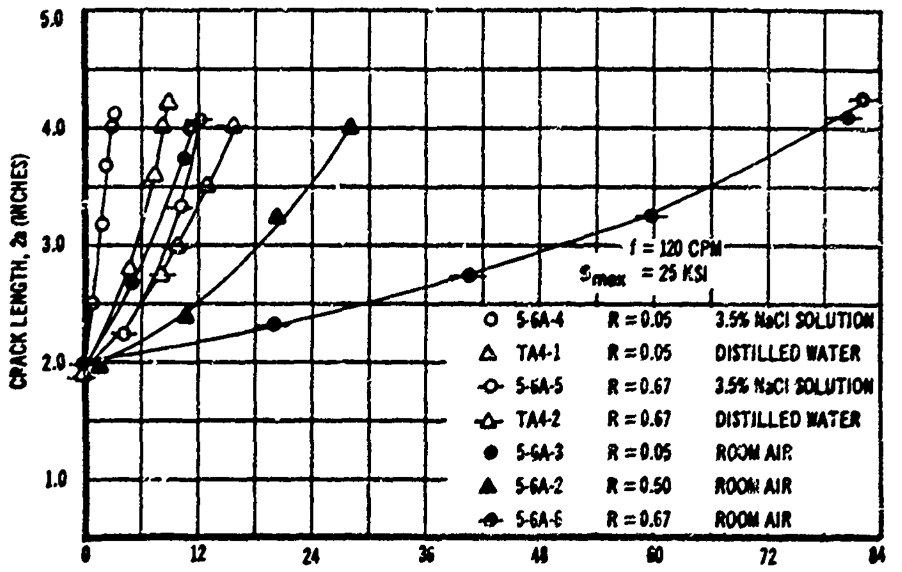

FIGURE 5-0.4.1-17. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, MILL-ANNEALED, 0.063-INCH-THICK (73)

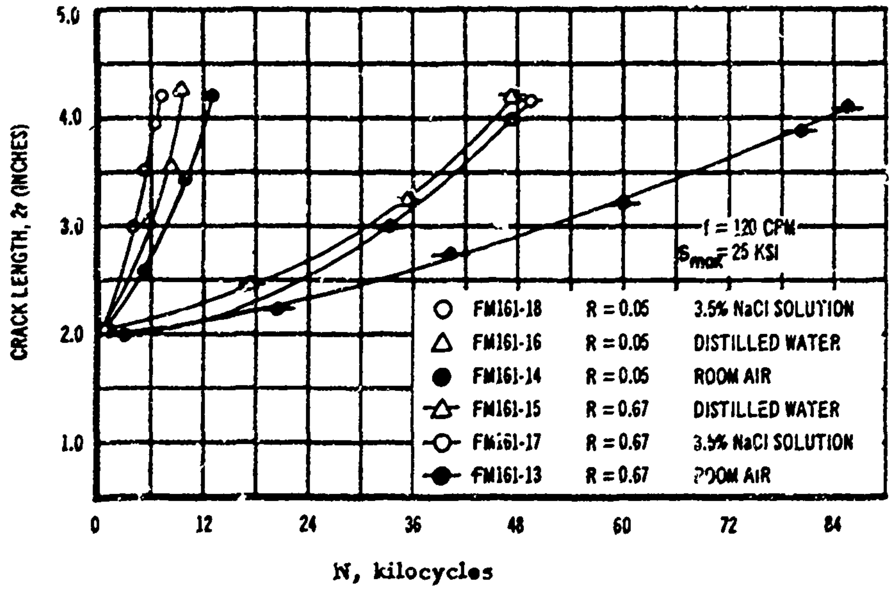

FIGURE 5-0.4.1-18. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, DUPLEX ANNEALED, 0.133-INCH-THICK (73)

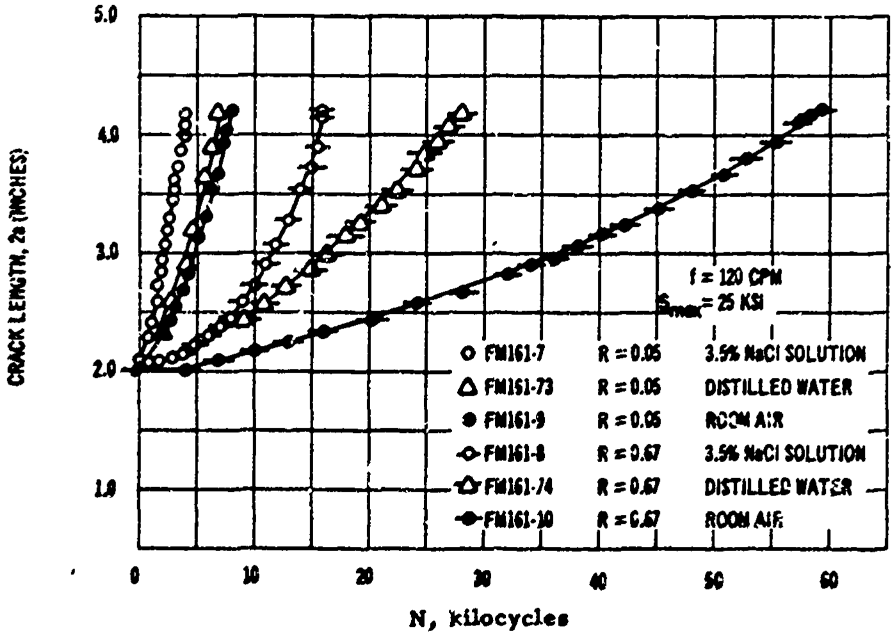

FIGURE 5-0.4.1-19. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, MILL-ANNEALED, 0.125-INCH-THICK (73)

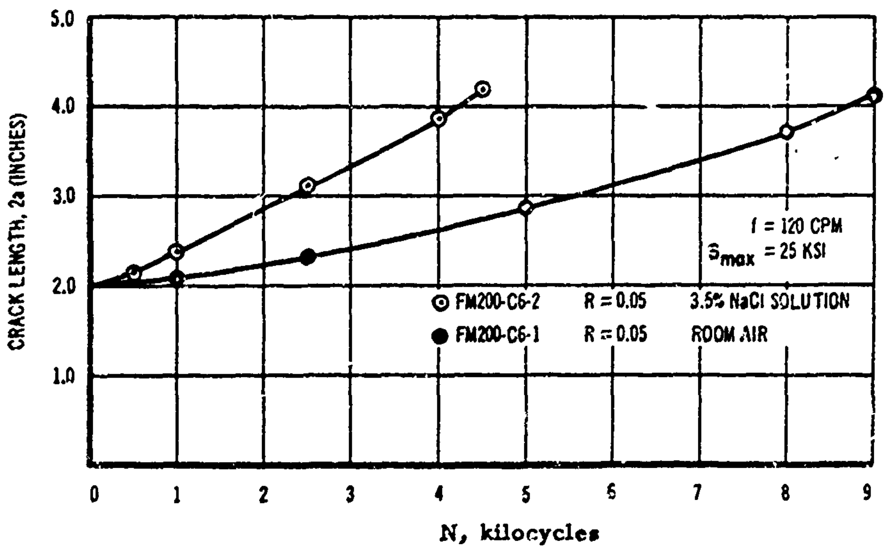

FIGURE 5-0.4.1-20. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, DUPLEX-ANNEALED, 0.133-INCH-THICK (73)

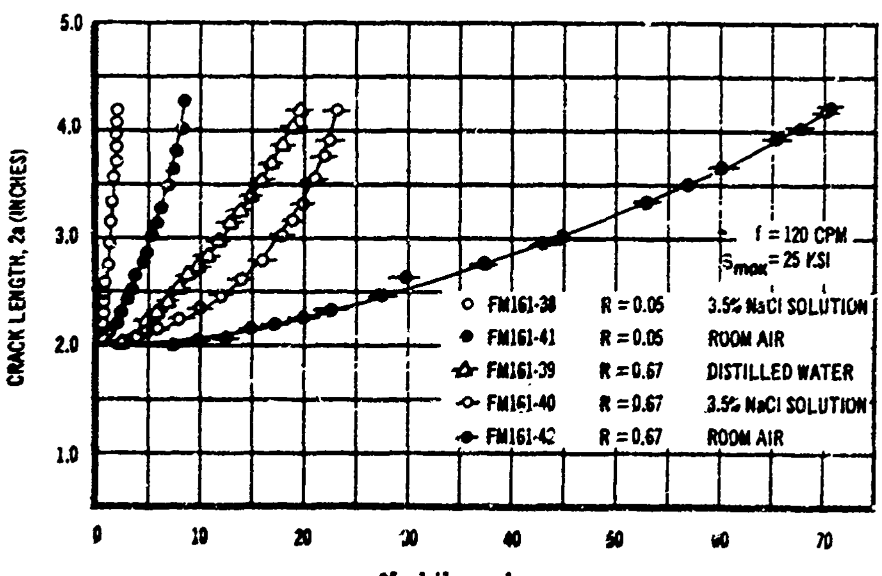

FIGURE 5-0.4.1-21. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, DUPLEX-ANNEALED, 0.133-INCH-THICK (73)

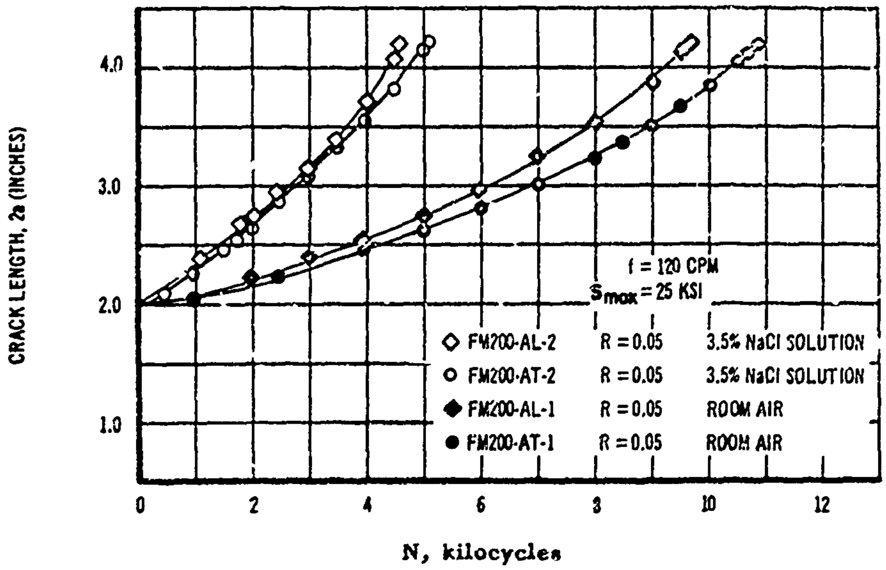

FIGURE 5-0.4.1-22. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, BETA-STA-1250, 0.133-INCH-THICK (73)

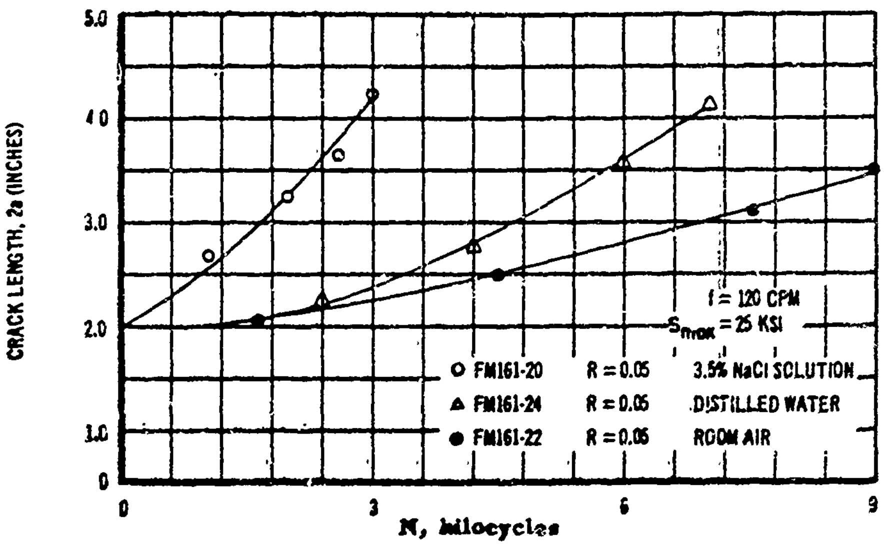

FIGURE 5-0.4.1-23. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, BETA-STA-1250, 0.133-INCH-THICK (73)

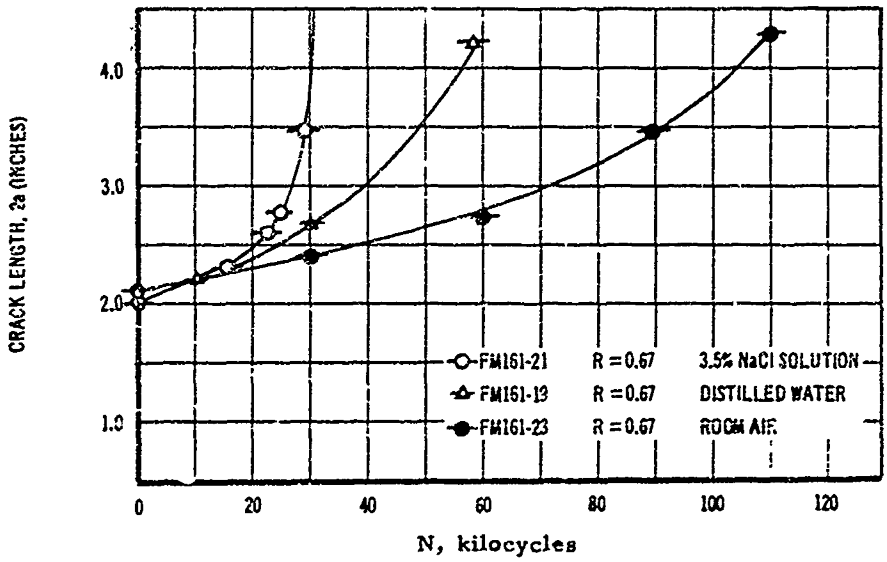

FIGURE 5-0.4.1-24. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, BETA-STA-1250, 0.133-INCH THICK (73)

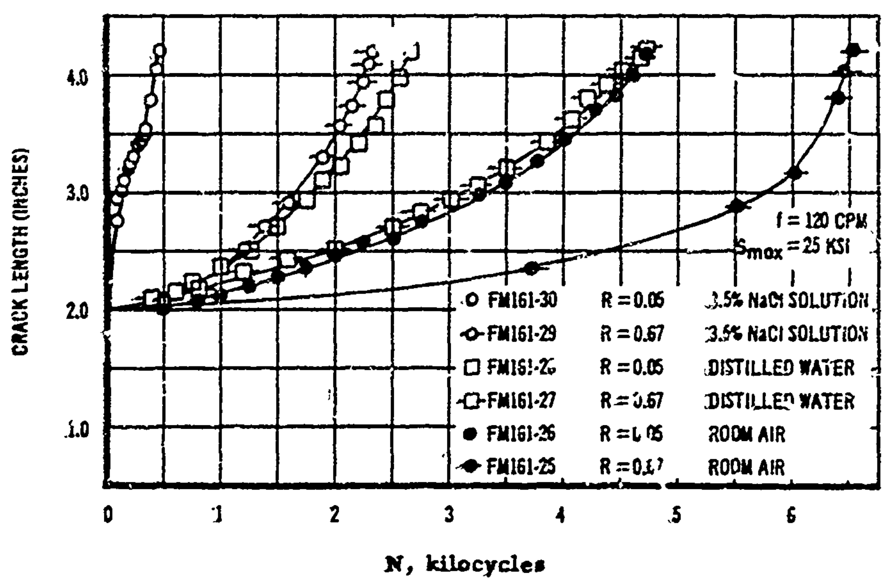

FIGURE 5-0.4.1-25. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, BETA-STA-1000, 0.25-INCH-THICK (73)

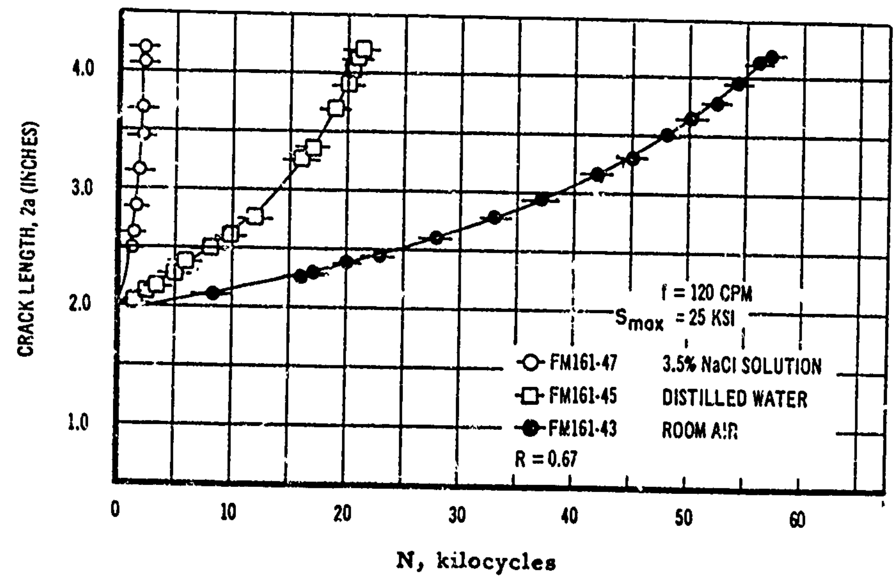

FIGURE 5-0.4.1-26. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, BETA-STA-1250, 0.25-INCH-THICK (73)

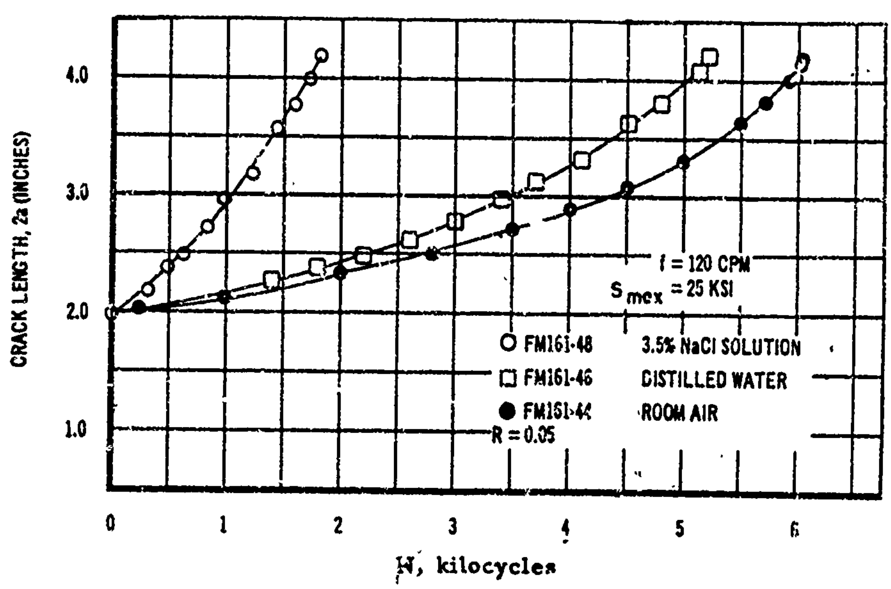

FIGURE 5-0.4.1-27. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, BETA-STA-1250, 0.25-INCH-THICK (73)

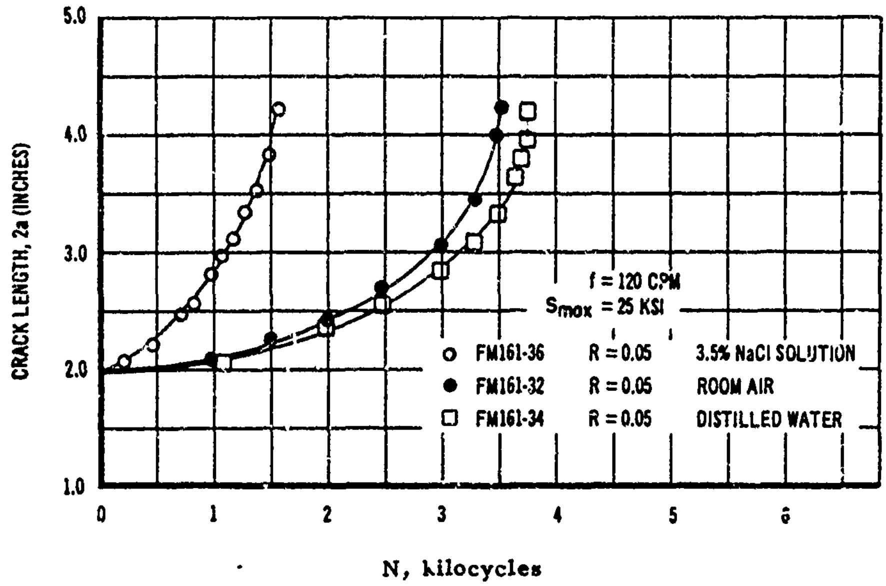

FIGURE 5-0.4.1-28. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, BETA-STA-1000, 0.5-INCH-THICK (73)

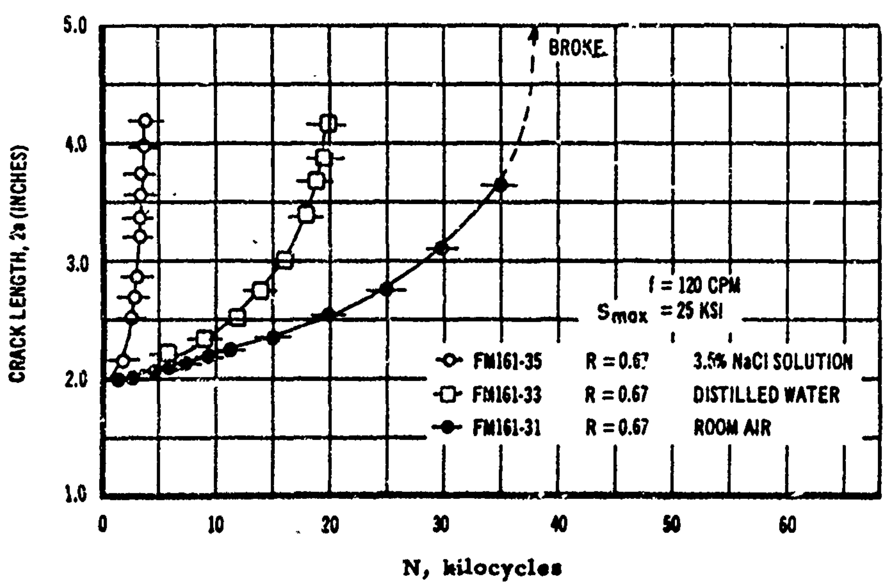

FIGURE 5-0.4.1-29. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, BETA-STA-1000, 0.5-INCH-THICK (73)

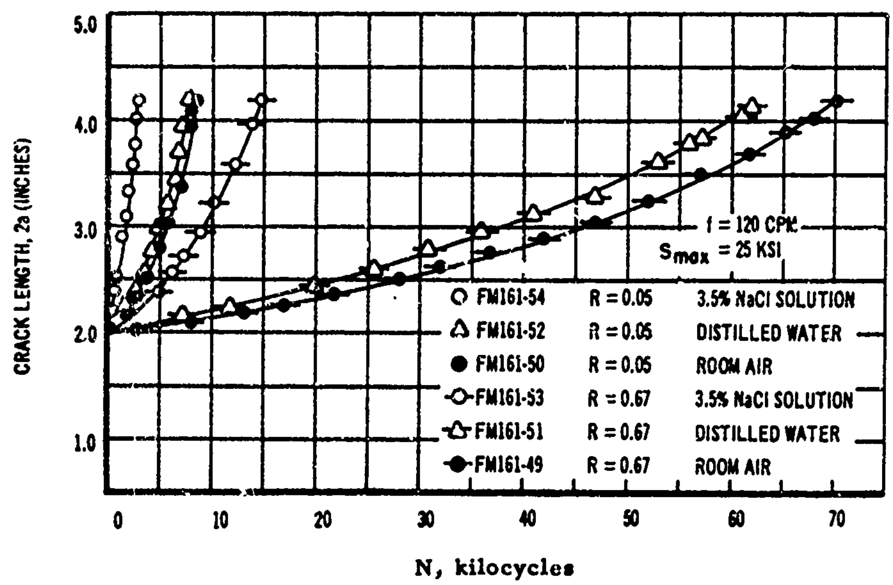

FIGURE 5-0.4.1-30. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-6Al-4V, BETA-STA-1250, 0.500-INCH-THICK (73)

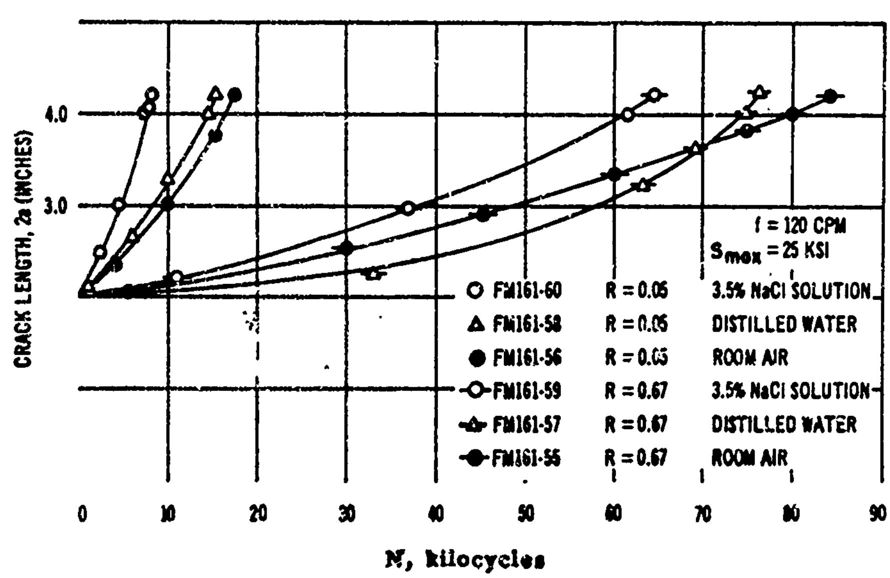

FIGURE 5-0.4.1-31. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-4Al-3Mo-1V, DUPLEX-ANNEALED, 0.500-INCH-THICK (73)

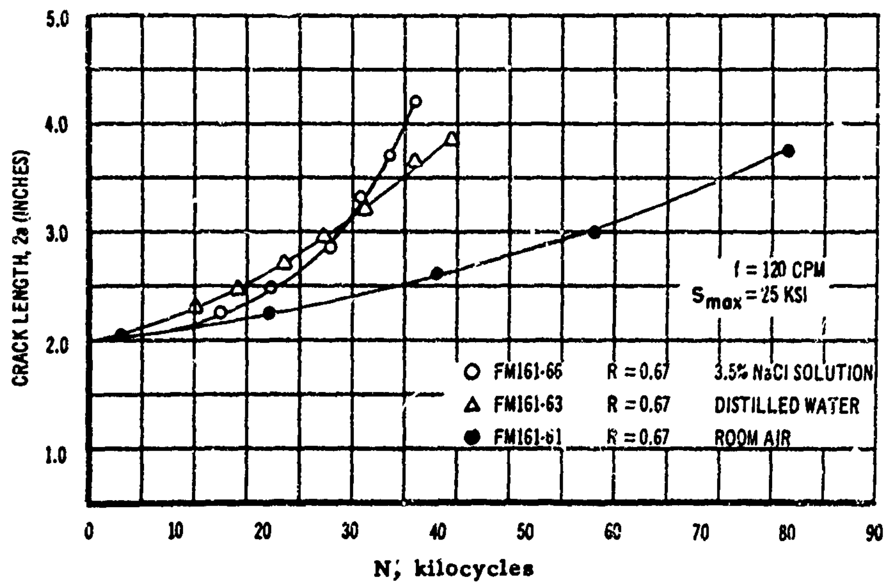

FIGURE 5-0.4.1-32. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-4Al-3Mo-1V, BETA-STA-1150, 0.16-INCH-THICK (73)

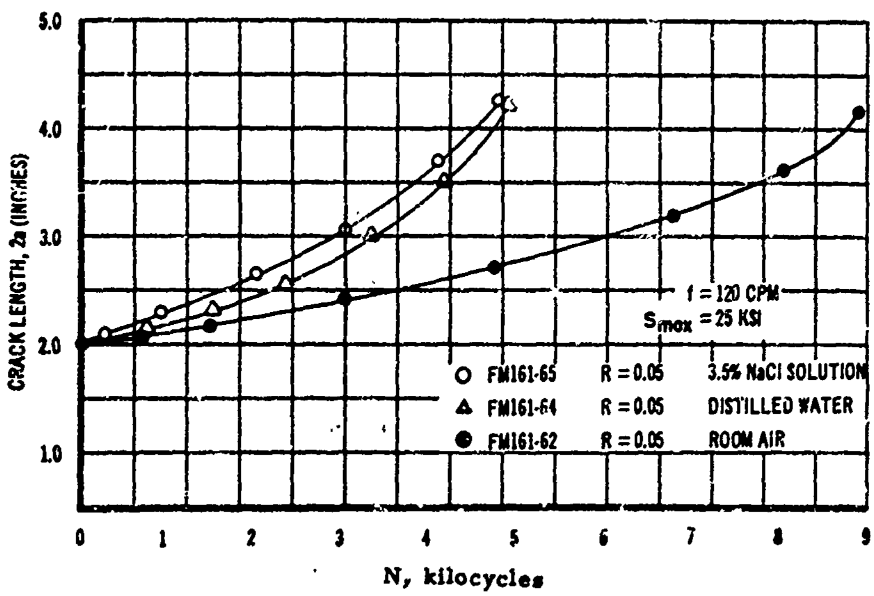

FIGURE 5-0.4.1-33. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-4Al-3Mo-1V, BETA-STA-1150, 0.16-INCH-THICK (73)

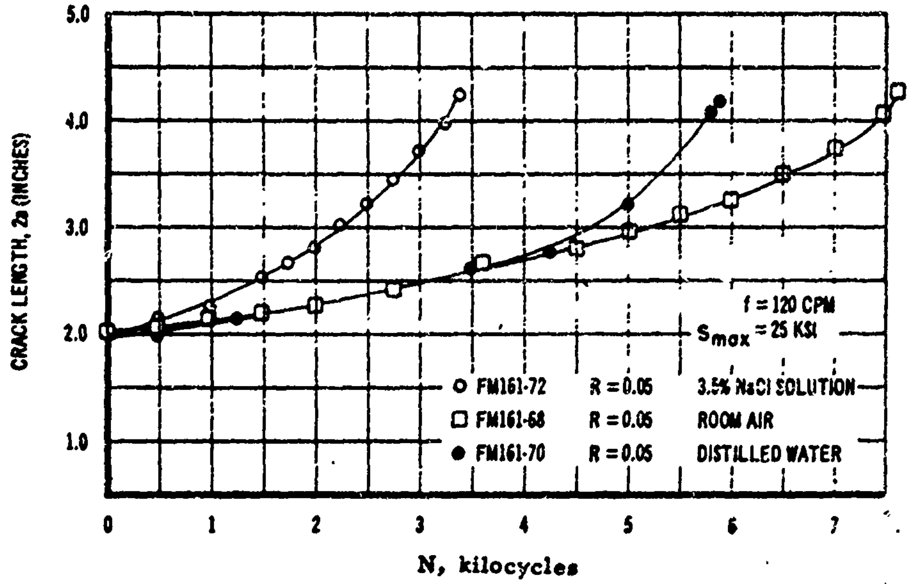

FIGURE 5-0.4.1-34. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-4Al-3Mo-1V, BETA-STA-1150, 0.500-INCH-THICK (73)

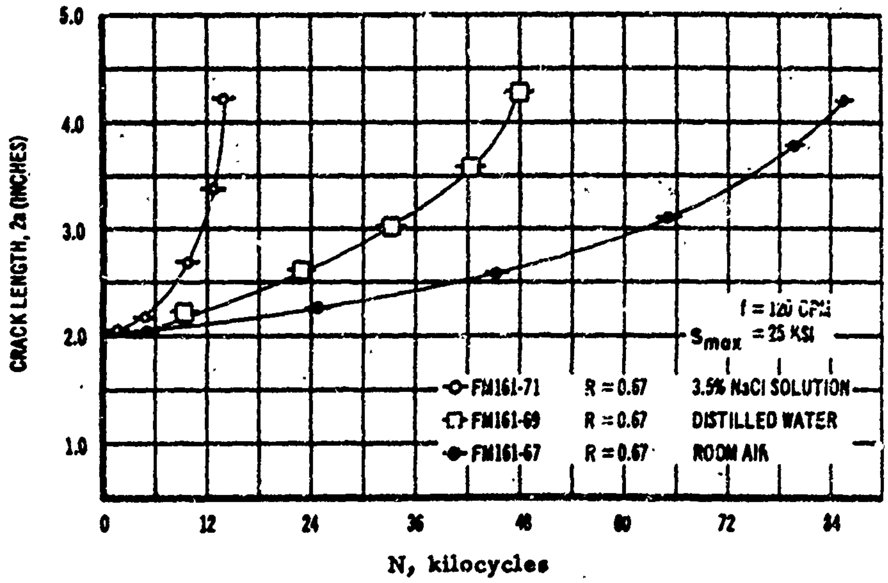

FIGURE 5-0.4.1-35. FATIGUE-CRACK GROWTH BEHAVIOR OF Ti-4Al-3Mo-1V, BETA-STA-1150, 0.500-INCH-THICK (73)

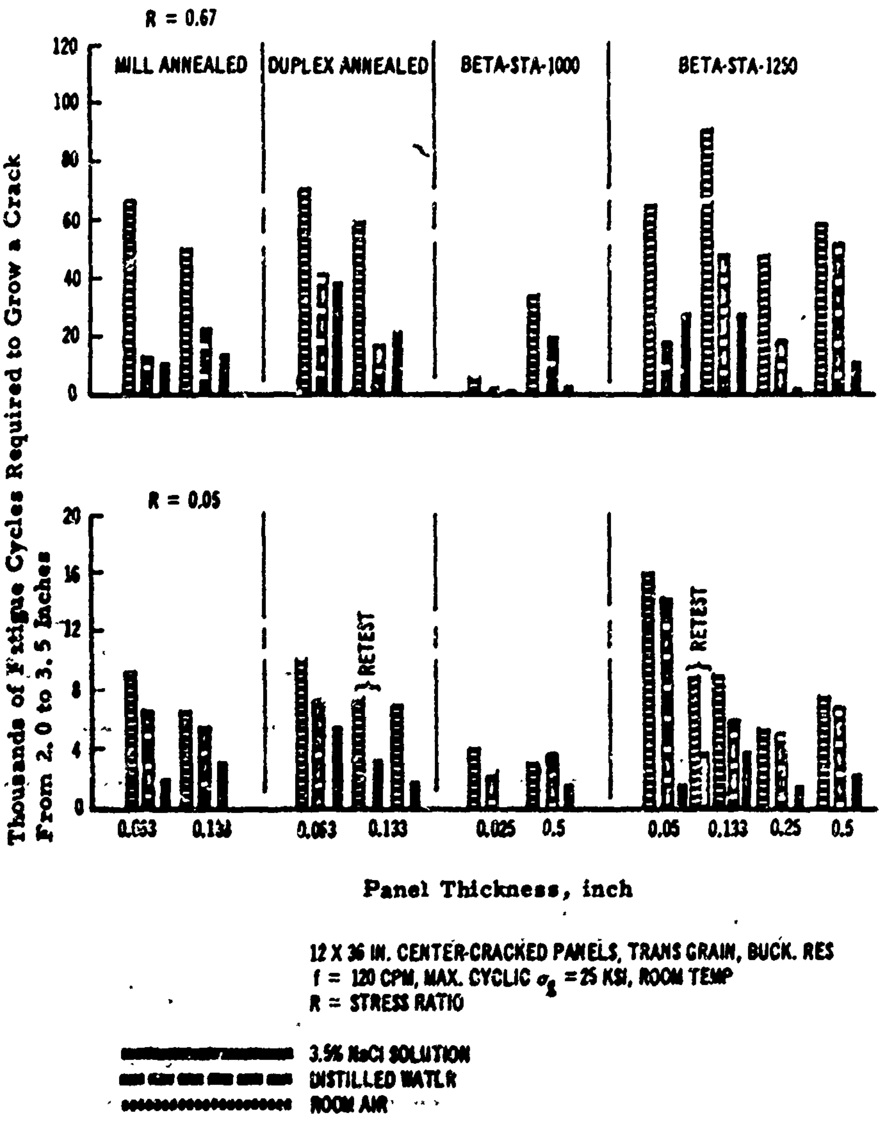

FIGURE 5-0.4.1-36. COMPARISON OF ENVIRONMENTAL FATIGUE-CRACK GROWTH RESULTS FOR Ti-6Al-4V (73)

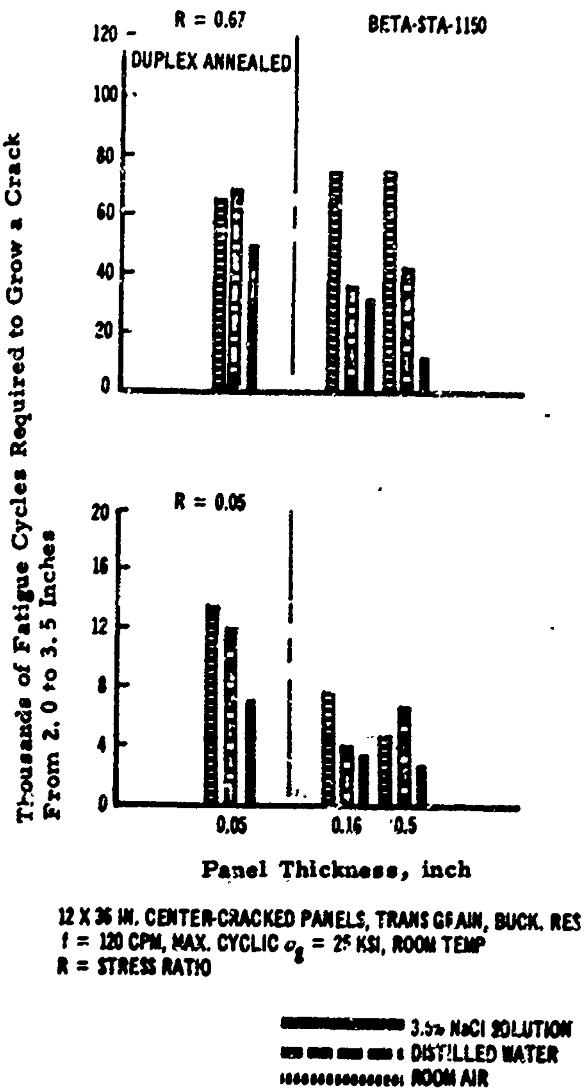

FIGURE 5-0.4.1-37. COMPARISON OF ENVIRONMENTAL FATIGUE-CRACK GROWTH RESULTS FOR Ti-4Al-3Mo-1V[73]

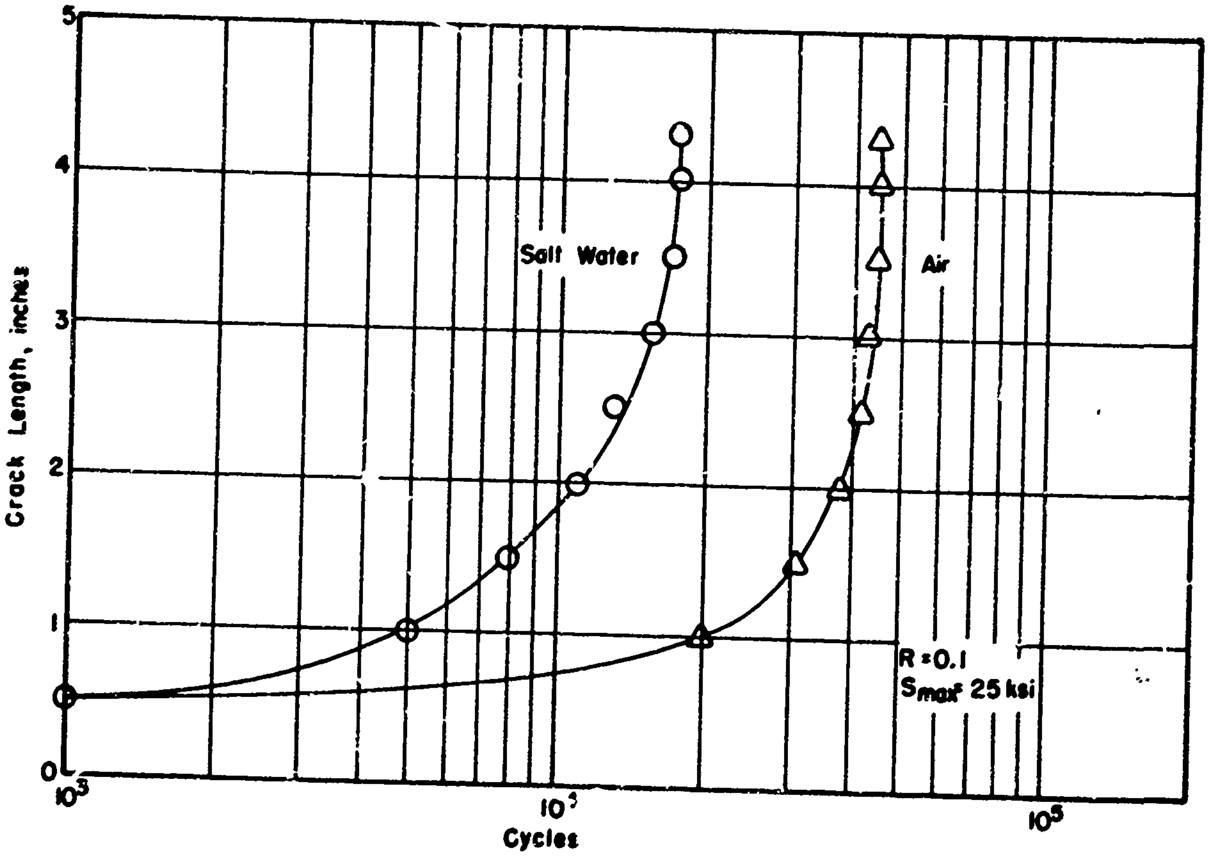

Fig. 5-0.4.1-38 Crack Growth Rate of 0.030" Duplex Annealed Ti-8-1-1 Sheet Material in Air and Salt Water (Precracked 8" x 24" Panels) (74)

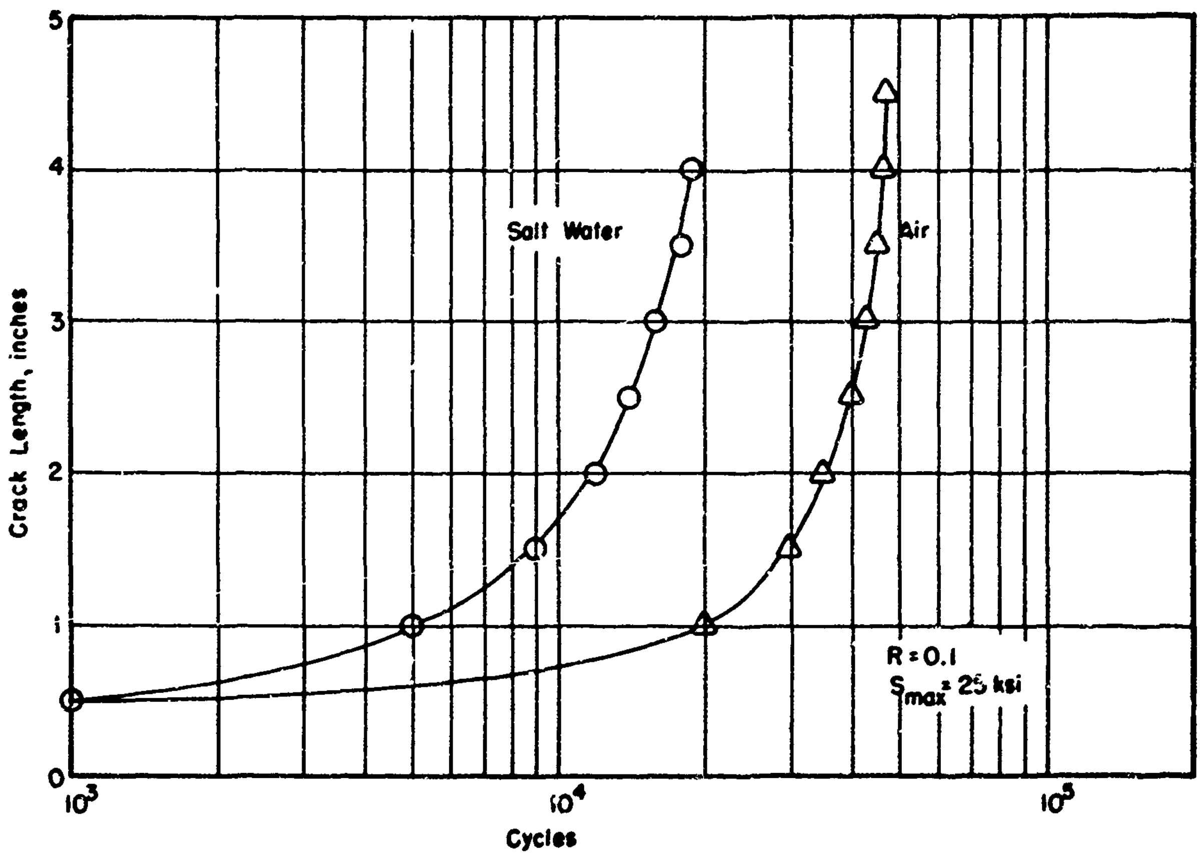

Fig. 5-0.4.1-39 Crack Growth Rate of 0.040" Mill Annealed Ti-6-4 Sheet Material in Air and Salt Water (Precracked 8" x 24" Panels) (74)

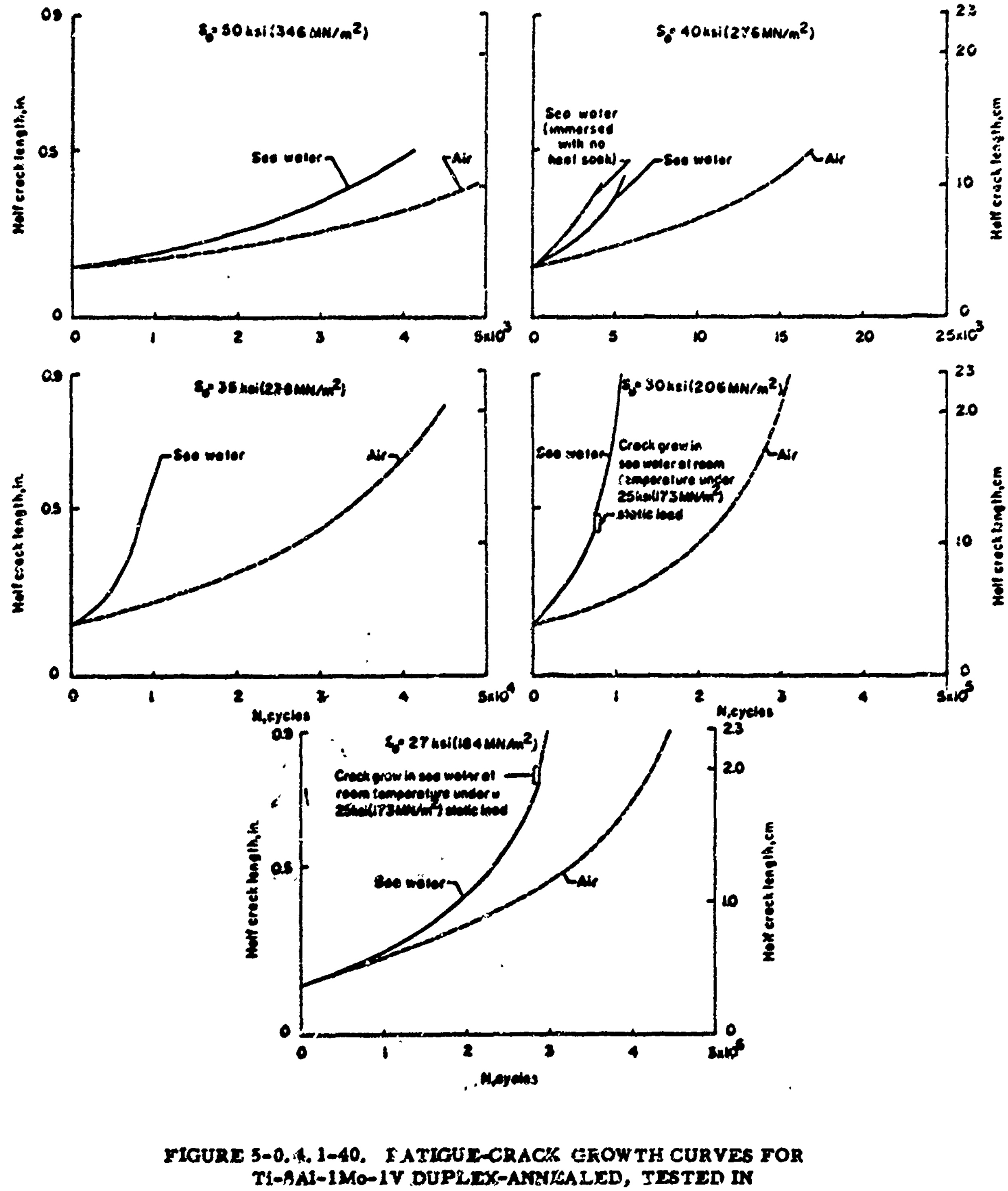

FIGURE 5-0.4.1-40. FATIGUE-CRACK GROWTH CURVES FOR Ti-8Al-1Mo-1V DUPLEX-ANNEALED, TESTED IN AIR OR UNDER ALTERNATE THERMAL AND SEAWATER SOAKING. S_m = 25-ksi (173 MN/m^2) (t = 0.050 inch) (75)

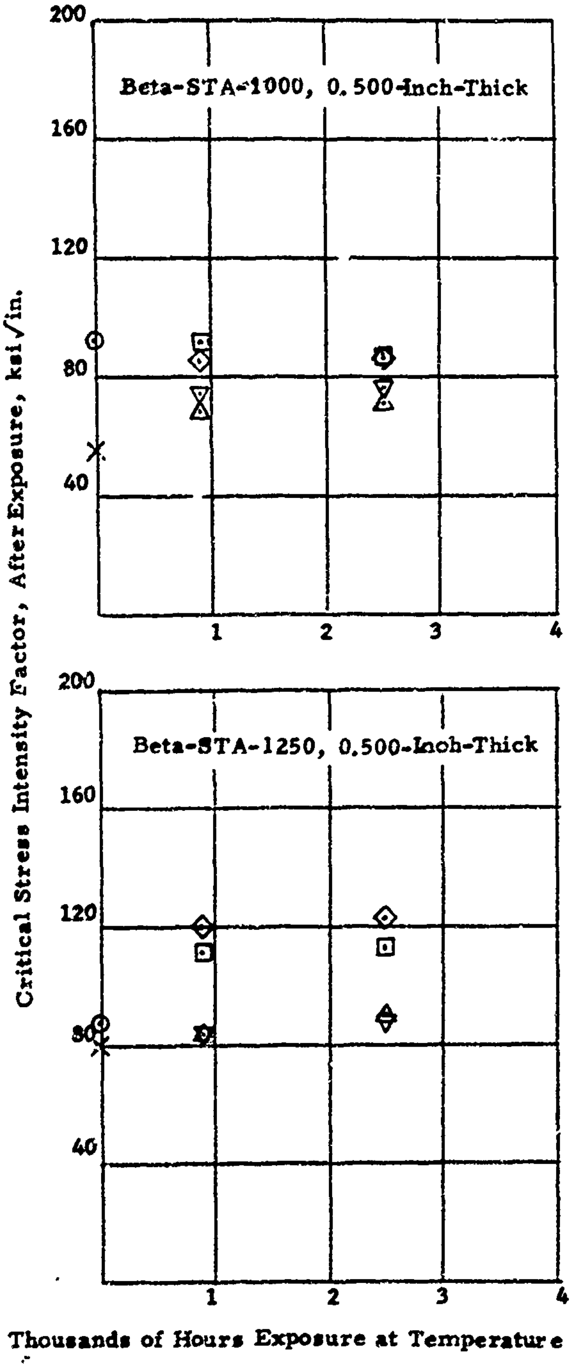

FIGURE 5-0.4.2-1. EFFECT OF UNSTRESSED THERMAL EXPOSURE ON DELAYED FRACTURE OF Ti-6Al-4V PLATE NOTCH BEND SPECIMENS(73)

Transverse Grain Direction

EXPOSURE TEMPERATURE	ROOM	450° F	550° F
FRACTURED IN AIR, K_{Ic}	○	□	◇
FRACTURED IN SALTWATER, K_{Ii}, 6-HOUR EXPOSURE	×	▽	△

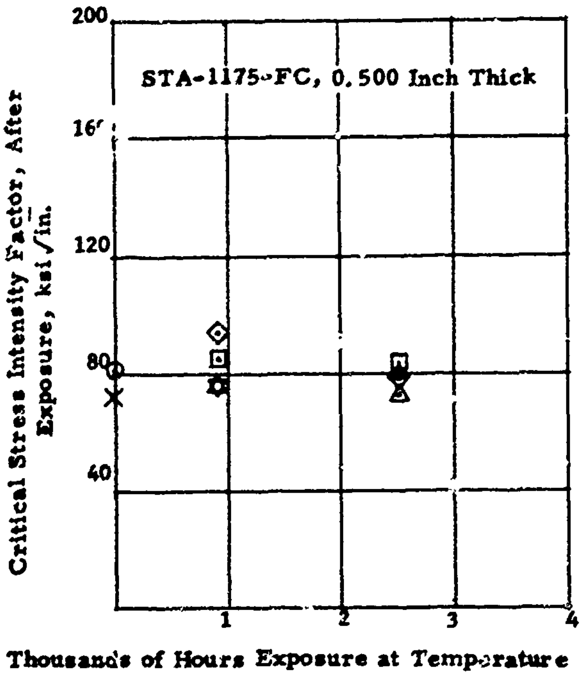

FIGURE 5-0.4.2-2. EFFECT OF UNSTRESSED THERMAL EXPOSURE ON DELAYED FRACTURE OF Ti-4Al-3Mo-1V PLATE NOTCH BEND SPECIMENS.(73)

Transverse Grain Direction

TABLE 5-0.4.2-1. SUMMARY OF PLANE-STRAIN FRACTURE-TOUGHNESS DATA[69,73,76,77](a)

Grain Direction:				Longitudinal			
Specimen Type:				Notch Bend			
Test Temperature:				Room			
Material	Product	Heat Treatment[(b)]	Thickness, inch	TUS	TYS	K_{Ic}	K_{Ii}
Ti-6Al-4V	Plate	MA	0.25				
		DA	0.25				
		β-STA-1000	0.500				
		β-STA-1250	0.500				
	Tee Extrusion (beta processed)	MA	0.50-1.00	142.3	124.3	89.6	65
		STA-1000	0.50-1.00	163.5	146.9	65.8	46
		STA-1250	0.50-1.00	154.4	139.4	77.8	60
	Angle Extrusion (beta processed)	MA	0.25-0.50	141.8	128.9	83.3	73
		STA-1000	0.25-0.50	160.0	145.7	67.3	51
		STA-1250	0.25-0.50	151.1	140.3	71.5	70
	Forging	β-Anneal	0.70	142.1	128.7	90.7	
		α+β -Anneal	0.70	144.6	[illegible]	56.3	
		β-STA-1000	0.70	167.8	148.0	69.8	
		α+β-STA-1000	0.70	167.1	154.3	45.2	
Ti-4Al-3Mo-1V	Plate	DA	0.500				
		β-STA-1150	0.500				
		β-STA-1050	0.500				
Ti-8Al-1Mo-1V	Plate	DA	0.25	130[(e)]	120[(e)]	127	31[(c)]
		DA	0.50	130[(e)]	120[(e)]	111	37[(c)]

(a) TUS, TYS, and K_{Ic} are average values of from one to four specimens, generally one heat. Units are ksi (1000 psi) for TUS and TYS; ksi-$\sqrt{in}$ for K_{Ic} and K_{Ii}.

K_{Ii} is an estimated minimum value after 6 hours' exposure, interpolated from time plots of sustained load tests.

(b) Heat treatments are described in Section 5-4.0 for Ti-6Al-4V and in Section 5-3.0 for Ti-8Al-1Mo-1V.

(c) Three-hour exposure time in salt water.

(d) Average of four heats within MIL-T-9046 specification chemistry.

(e) Tentative A values for MIL-HDBK-5.

TABLE 5-0.4.2-1 Continued

Transverse											
Notch Bend				Surface Flaw							
Room Temperature				Room Temperature				-65° F			
TUS	TYS	K_{Ic}	K_{Ii}	TUS	TYS	K_{Ic}	K_{Ii}	TUS	TYS	K_{Ic}	K_{Ii}
149.0	141	83	27[c]								
149.8	142.9	69.2	53								
168.9[d]	150.[illegible][d]	82.8[d]	64[d]		135	88.6	80.0		153	104.6	
152.8[d]	140.4[d]	88.4[d]	73.8[d]		151	84.0	58.0		167	82.1	
143.6	127.1	94.0									
168.2	149.0	73.1									
155.0	140.3	81.3									
143.3	126.8	89.4									
141.5	130.8	77.7									
164.0	147.0	67.1									
167.8	154.0	46.6									
138.0	126.2	124.9	120								
[illegible]4.8	137.2	96.3	77		134	87.9	77		154	87.3	
[illegible]75.0	154.5	75.9	64								
130[e]	120[e]	111	25[c]								

TABLE 5-0.4.2-2. SUMMARY OF RESIDUAL STRENGTH DATA(73,78)(a)(c)

Grain Direction:								
Specimen Type:				Center				
Test Temperature:				Room				
Material	Product	Treatment(b)	Thickness, inch	TUS	TYS	F_g	F_{gsw}	K_c
Ti-6Al-4V	Strip	MA	0.021	147	135	77(d)	65(d)	140(d)
	Sheet	MA	0.060	143.8	137.7	58		158
		MA	0.125	137.5	133.0	63.2		172
		DA	0.060	131.5	125.3	48.1		131
		DA	0.125	142.0	132.1	60.1		168
		β-STA-1250	0.050	152.5	147.1	41.8		115.2
		β-STA-1250	0.125	157.1	139.0	49.5		134.0
	Plate	β-STA-1000	0.250	174.3	157.9	46.0		124
		β-STA-1000	0.500	172.0	155.0	30.0		81
		β-STA-1250	0.250	159.9	145.7	38.8		105.5
		β-STA-1250	0.500	159.5	142.2	47.3		129
Ti-4Al-3Mo-1V	Sheet	DA	0.050	127.1	118.3	71.8		194.8
		β-STA-1150	0.160	151.7	134.8	46.7		126.8
	Plate	β-STA-1150	0.500	168.6	146.7	33.7		92.1
Ti-8Al-1Mo-1V	Strip	MA	0.016	146	129	78(d)	66(d)	142(d)

(a) TUS, TYS, Fg and Kc are average values of up to five heats.

- F_{gsw} and K_{csw} are estimated minimum values after six hours' exposure.

(b) Heat treatments are described in Section 5-4.0 for Ti-6Al-4V and in Section 5-3.0 for Ti-8Al-1Mo-1V.

TABLE 5-0.4.2-2 Continued

Transverse							Longitudinal					
Cracked Specimen							Center Cracked Specimen					
	-65° F						Room					
K_{csw}	TUS	TYS	F_g	F_{gsw}	K_c	K_{csw}	TUS	TYS	F_g	F_{gsw}	K_c	K_{csw}
119(d)							14[illegible](d)	125(d)	57(d)	48(d)	104(d)	88(d)
159	160.0	154.4	47.9		130							
138	155.8	152.4	50.1		132							
128	143.6	136.5	46.1		125							
130	158.0	153.1	56.9		157							
103	173.5	165.9	36.5		99.1							
101	172.4	157.5	39.0		106							
46	187.1	166.7	25.1		68.3							
57	189.5	173.8	28.3		76.8							
	173.5	170.7	35.7		96.8							
90	176.9	164.6	43.1									
	142.7	133.4	69		187							
101	171.7	152.7	43.1		117							
60	184.6	163.5	30.4		82.3							
120(d)							152	136	72(d)	58(d)	131(d)	106(d)

(c) 12 x 36-inch specimen with 4.2-inch fatigue crack except as noted by footnote d. TUS, TYS, F_g and F_{gsw} are reported in units of ksi (1000 psi); for K_c and K_{csw} the units are ksi-$\sqrt{in}$.

(d) 8 x 24-inch specimen with 2-inch fatigue crack. F_{gsw} and K_{csw} are for 3-hour exposure time in salt water.

EXPOSURE TEMPERATURE	ROOM	500° F	550° F
FRACTURED IN AIR	○	□	◇
FRACTURED IN SALTWATER · 3-HOUR EXPOSURE	×	▽	△

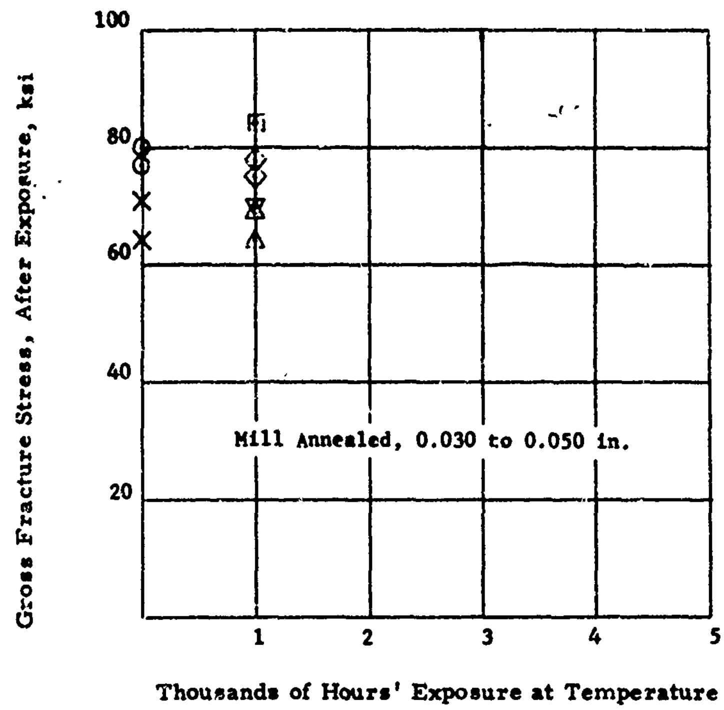

FIGURE 5-0.4.2-3 EFFECT OF UNSTRESSED THERMAL EXPOSURE ON DELAYED FRACTURE OF 8-INCH-WIDE Ti-6Al-4V SHEET SPECIMENS WITH A 2-INCH CRACK.(78)

Transverse Grain Direction

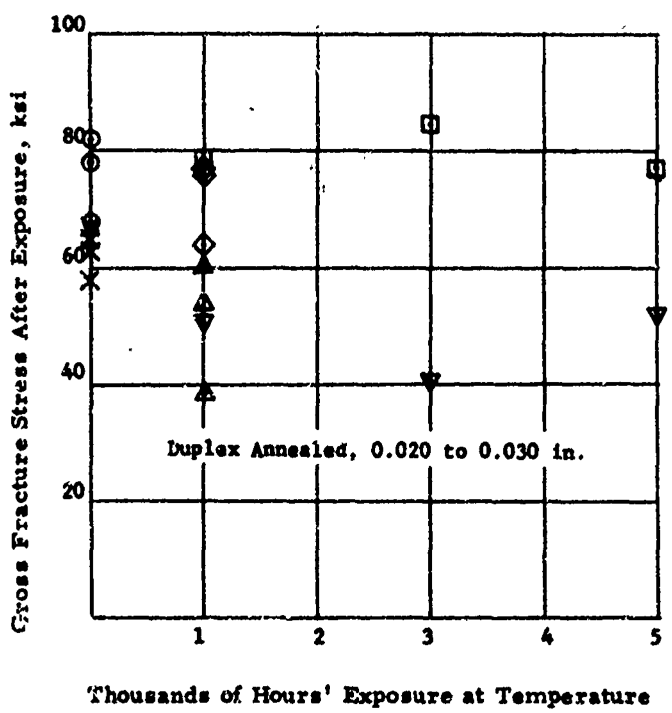

FIGURE 5-0.4.2-4 EFFECT OF UNSTRESSED THERMAL EXPOSURE ON DELAYED FRACTURE OF 8-INCH-WIDE Ti-8Al-1Mo-1V SHEET SPECIMENS WITH A 2-INCH CRACK.(78)

Transverse Grain Direction

5-1 Commercially Pure Titanium

5-1.0 SPECIFICATIONS AND FORMS

This section covers commercially pure titanium of the following specifications and forms:

Specification	Forms
MIL-T-9046	Sheet, strip, and plate
MIL-T-9047	Bars and forgings
MIL-H-81200	Heat treatment, all forms

5-1.1 ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES

Table 5-1.1-1 summarizes the design mechanical properties of commercially pure titanium at room temperature.

5-1.2 ENVIRONMENTAL EFFECTS

5-1.2.1 Elevated-Temperature Effects

The effect of temperature data are presented in Figures 5-1.2.1-1 through 5-1.2.1-6.

5-1.2.3 Stress-Strain and Tangent-Modulus Curves

Typical full-range stress-strain curves at room temperature for two grades are presented in Figures 5-1.2.3-1 and 5-1.2.3-2.

5-1.4 THERMOPHYSICAL EFFECTS

The effect of temperature on physical properties is displayed in Figures 5-1.4-1 through 5-1.4-4.

[illegible]

Alloy	MIL-T-9046 TYPE I			MIL-T-9047 TYPE I
	Composition A	Composition B	Composition C	Composition A
Form	Sheet, strip, and plate			Bars and forgings
Condition	Annealed			Annealed
Thickness or diameter, in.	---			≤3.0
Basis	S	S	S	S
Mechanical properties:				
F_{tu}, ksi	50	80	65	80
F_{ty}, ksi	40	70	55	70
F_{cy}, ksi	40	70	55	(70)
F_{su}, ksi	[illegible]	42	[illegible]	[illegible]
F_{bru}, ksi:				
(e/D = 1.5)	[illegible]	120	[illegible]	[illegible]
(e/D = 2.0)	[illegible]	--	[illegible]	[illegible]
F_{bry}, ksi:				
(e/D = 1.5)	[illegible]	101	[illegible]	[illegible]
(e/D = 2.0)	[illegible]	--	[illegible]	[illegible]
e, per cent:				
In 2 in.	[a]20	[a]15	[a]18	--
In 4 D	--	--	--	15
E, 10^6 psi	15.5			
E_c, 10^6 psi	16.0			
G, 10^6 psi	6.0			
μ	0.32			
n	--			
w, lb/in.^{3}	0.163			

Values in parentheses () are tentative values.

[a] Thickness 0.025 inch and over.

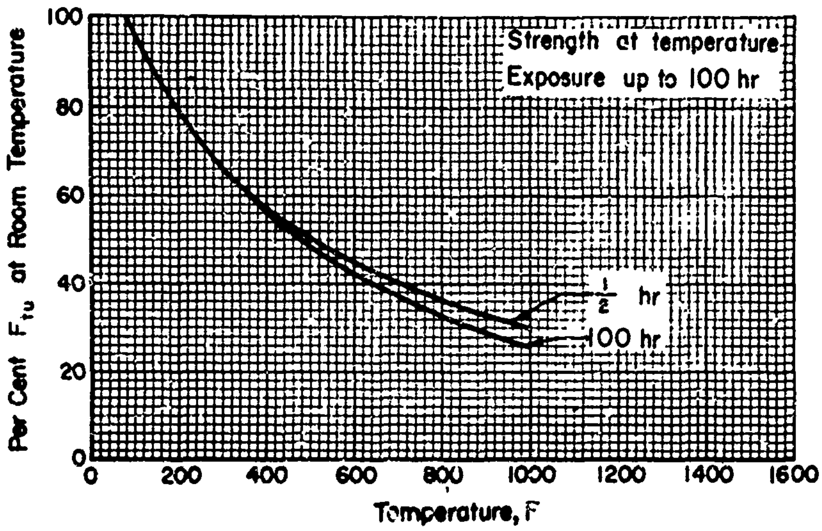

FIGURE 5-1.2.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF ANNEALED, COMMERCIALLY PURE TITANIUM

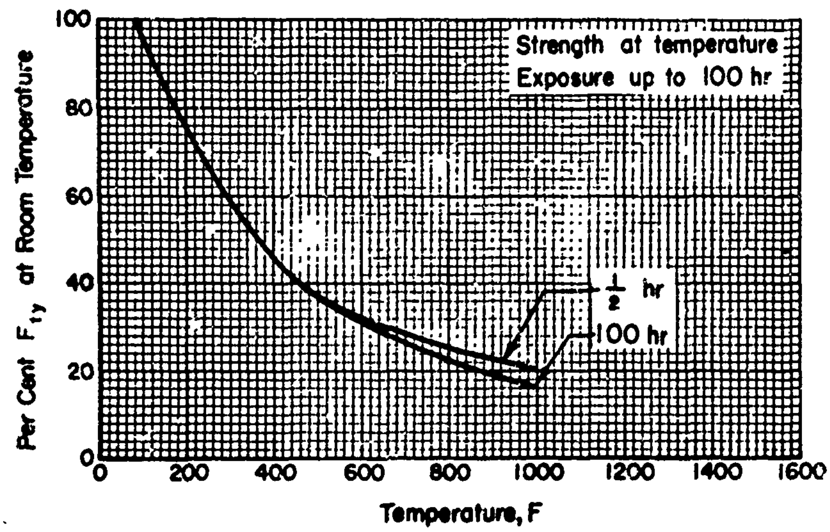

FIGURE 5-1.2.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF ANNEALED, COMMERCIALLY PURE TITANIUM

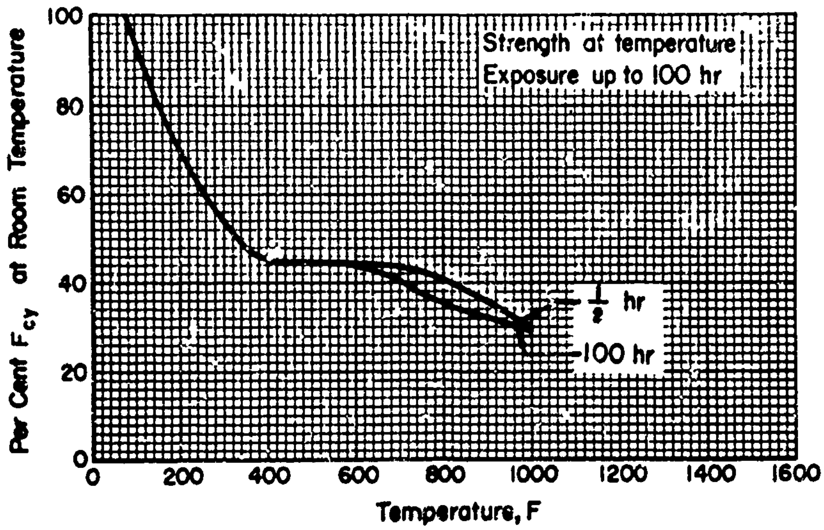

FIGURE 5-1.2.1-3. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF ANNEALED, COMMERCIALLY PURE TITANIUM

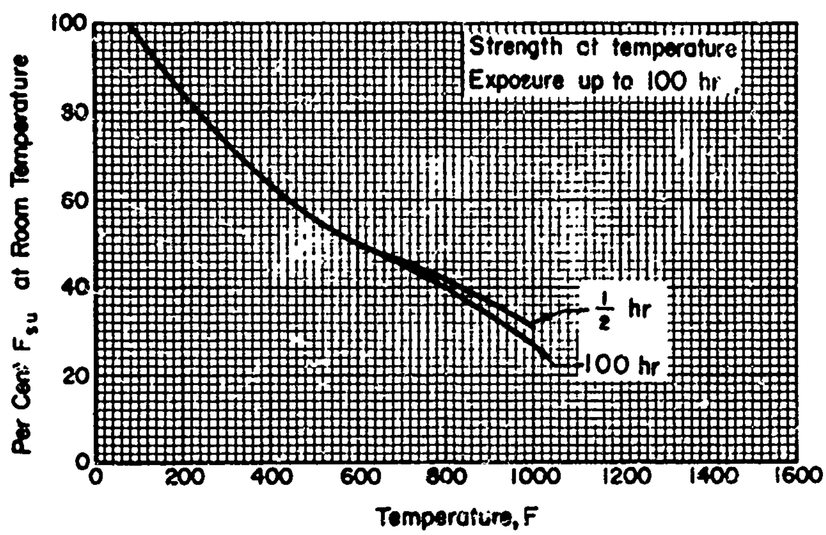

FIGURE 5-1.2.1-4. EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF ANNEALED COMMERCIALLY PURE TITANIUM

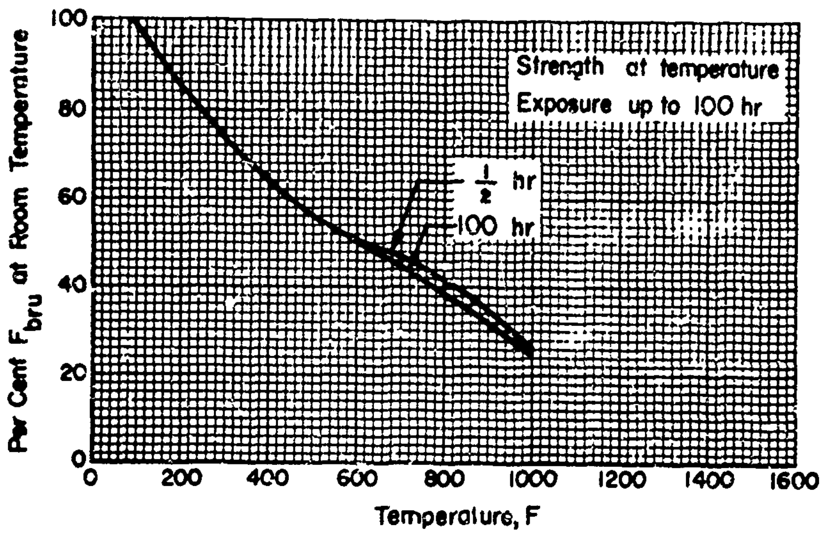

FIGURE 5-1.2.1-5. EFFECT OF TEMPERATURE ON THE ULTIMATE BEARING STRENGTH (F_{bru}) OF ANNEALED, COMMERCIALLY PURE TITANIUM

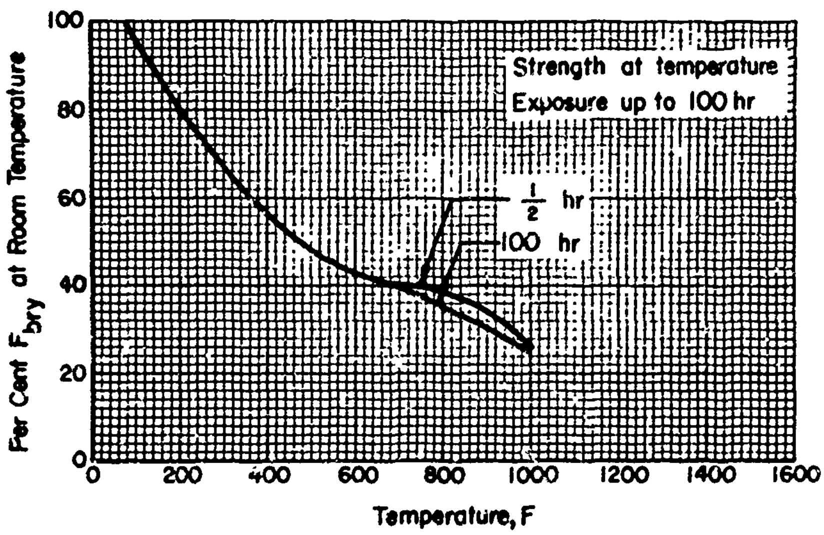

FIGURE 5-1.2.1-6. EFFECT OF TEMPERATURE ON THE BEARING YIELD STRENGTH (F_{bry}) OF ANNEALED, COMMERCIALLY PURE TITANIUM

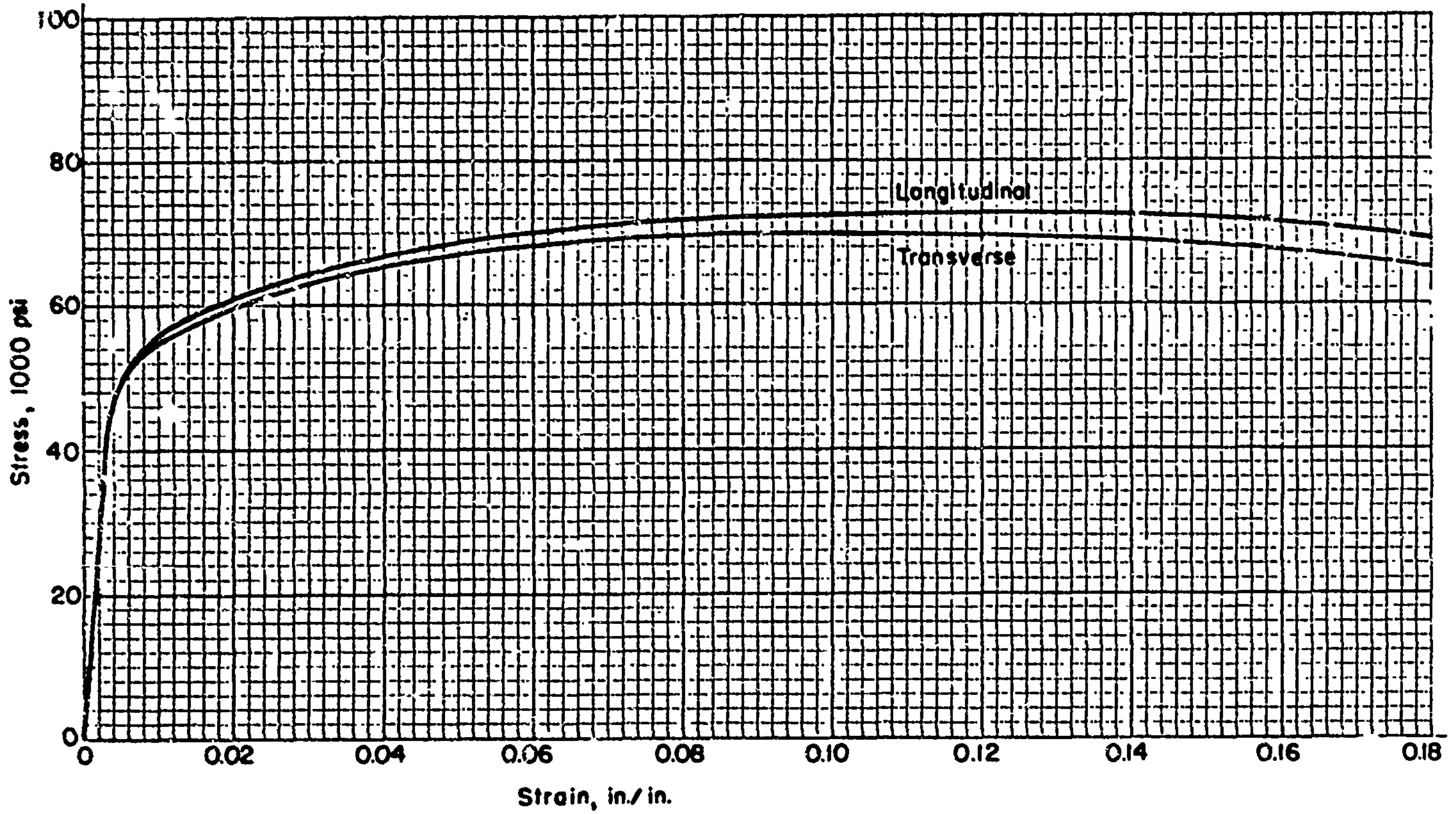

FIGURE 5-1.2.3-1. TYPICAL FULL-RANGE STRESS-STRAIN CURVES FOR COMMERCIALLY PURE TITANIUM SHEET (40-ksi yield) AT ROOM TEMPERATURE(47)

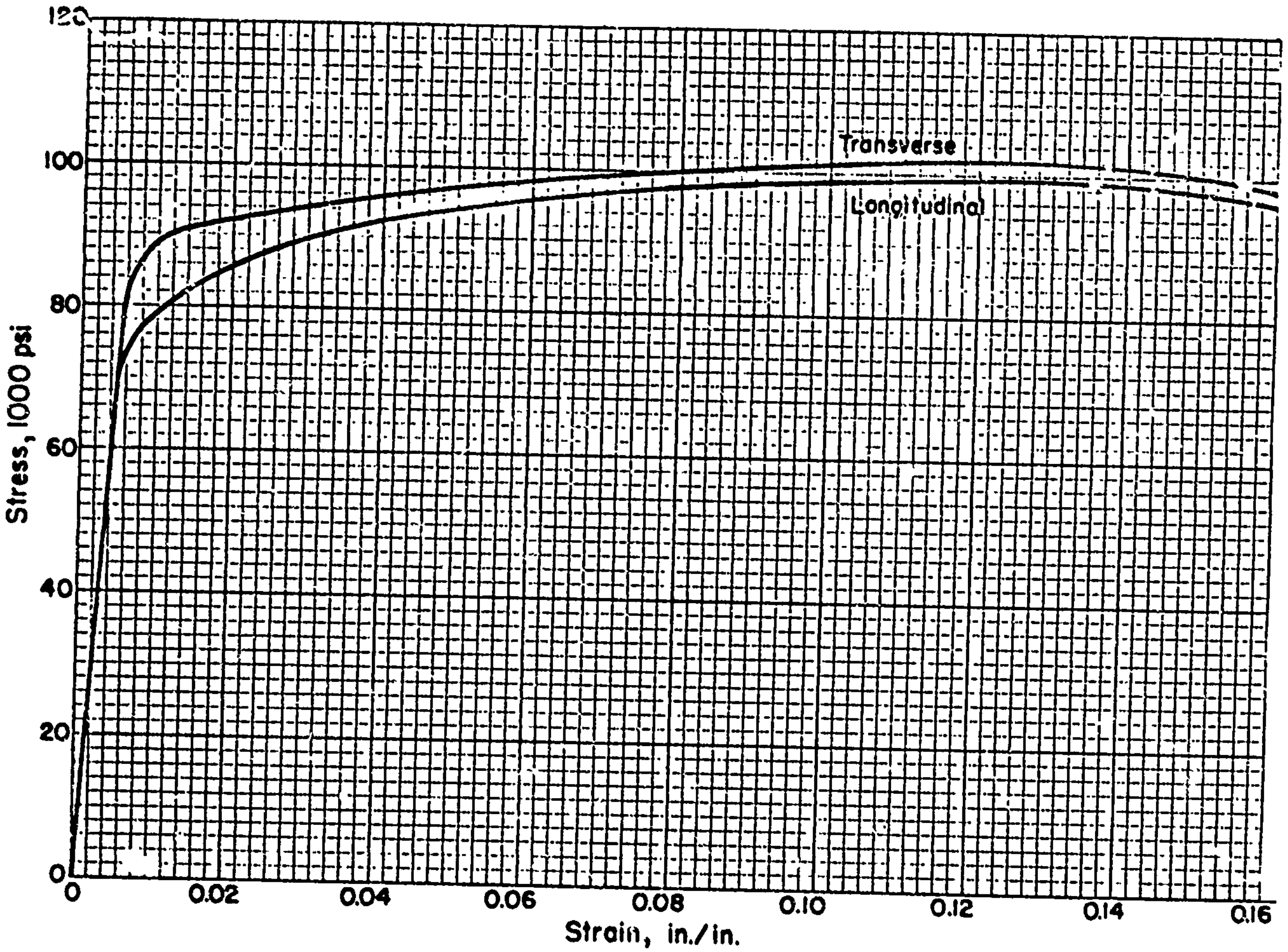

FIGURE 5-1.2.3-2. TYPICAL FULL-RANGE STRESS-STRAIN CURVES FOR COMMERCIALLY PURE TITANIUM SHEET (70-ksi yield) AT ROOM TEMPERATURE(47)

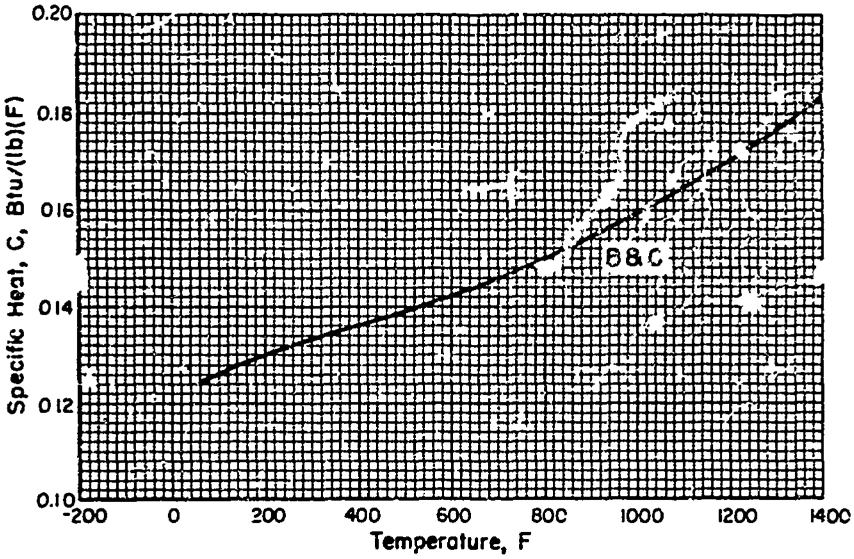

FIGURE 5-1.4-1. EFFECT OF TEMPERATURE ON THE SPECIFIC HEAT (C) OF COMMERCIALLY PURE TITANIUM, COMPOSITIONS B AND C(6)

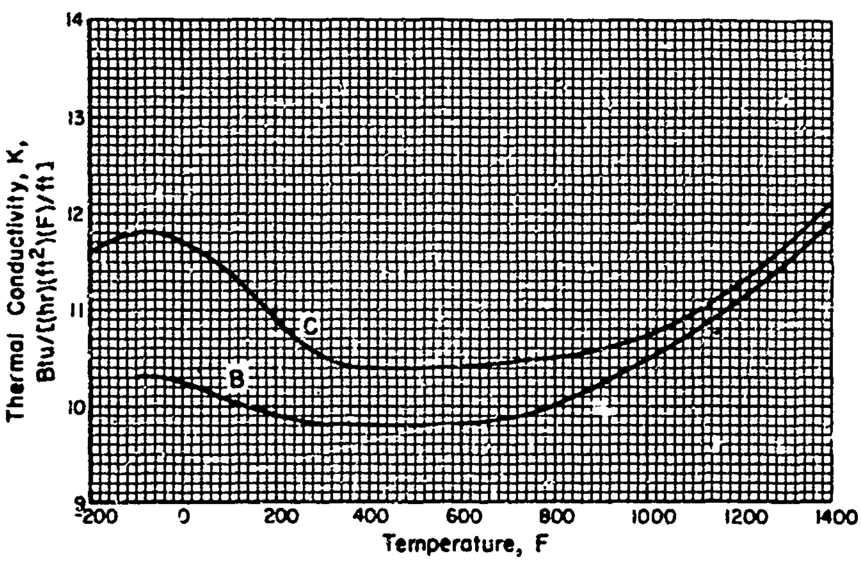

FIGURE 5-1.4-2. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY (K) OF COMMERCIALLY PURE TITANIUM, COMPOSITIONS B AND C(6)

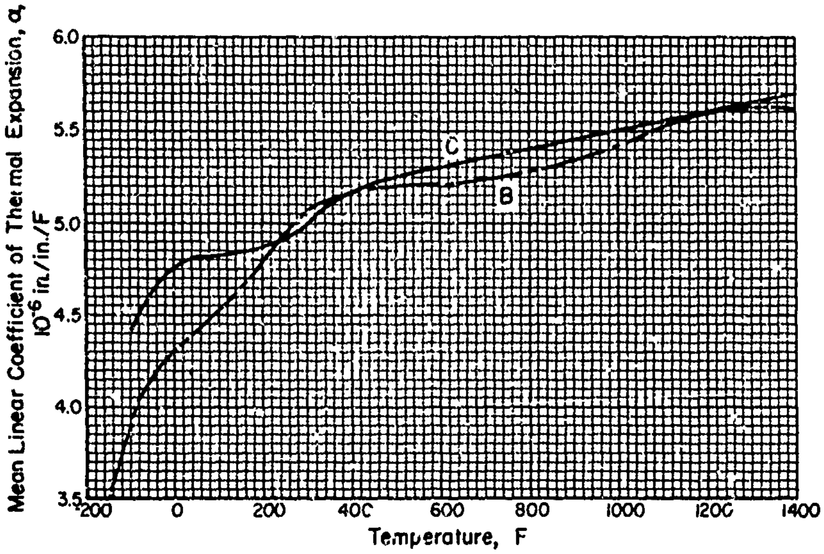

FIGURE 5-1.4-3. MEAN LINEAR COEFFICIENT OF THERMAL EXPANSION (α) OF COMMERCIALLY PURE TITANIUM, COMPOSITIONS B AND C, BETWEEN ROOM TEMPERATURE AND THE INDICATED TEMPERATURE[6]

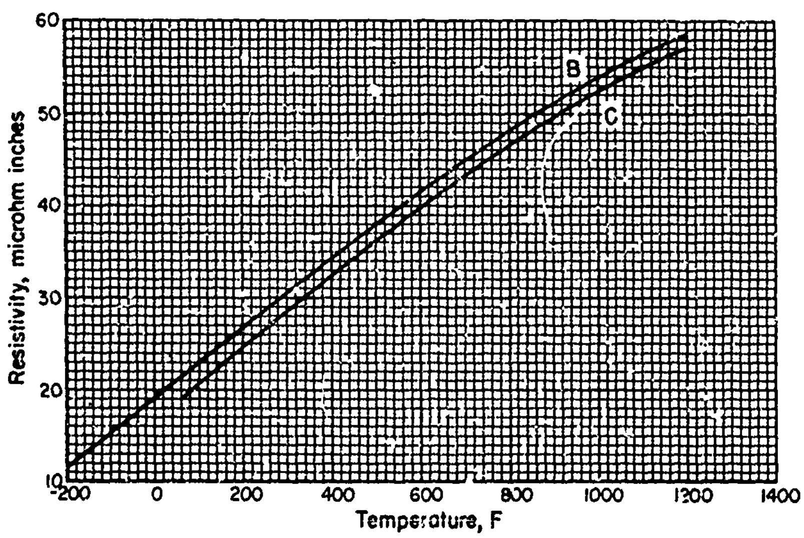

FIGURE 5-1.4-4. EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY (ρ) OF COMMERCIALLY PURE TITANIUM, COMPOSITIONS B AND C[6]

Note: The figures on this page differ from corresponding values in MIL-HDBK-5.

5-2 Titanium Alloy Ti-5Al-2.5Sn

5-2.0 SPECIFICATIONS AND FORMS

This section covers titanium alloy Ti-5Al-2.5Sn of the following specifications and forms:

Specification	Form
MIL-T-9046	Sheet, strip, and plate
MIL-T-9047	Bars and forgings
---	Extrusions
MIL-H-81200	Heat treatment, all forms

5-2.1 ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES

Table 5-2.1-1 summarizes the design mechanical properties of titanium alloy Ti-5Al-2.5Sn at room temperature.

5-2.2.4 Creep Effects

Creep data are presented in Figure 5-2.2.4-1.

5-2.2.5 Fatigue Effects

A constant-life diagram for fatigue behavior is presented in Figure 5-2.2.5-1.

5-2.4 THERMOPHYSICAL EFFECTS

Thermophysical effects data are presented in Figures 5-2.4-1 through 5-2.4-4.

5-2.2 ENVIRONMENTAL EFFECTS FOR ANNEALED MATERIAL

5-2.2.1 Elevated Temperature Effects

The effect of temperature data are presented in Figures 5-2.2.1-1 through 5-2.2.1-8.

Alloy	MIL-T-9046 F Type II Composition A				-9047D	Ti-5Al-2.5Sn
Form	Sheet		Plate		Bars, forgings	Extrusions
Condition	Annealed					
Thickness or diameter, in.	≤0.187		0.188-1.500	>1.500	<3.000	--
Basis	A	B	S	S	S	S[b]
Mechanical properties:						
F_{tu}, ksi	120	125			115	
F_{ty}, ksi	113	118			110	
F_{cy}, ksi						
F_{su}, ksi	75	78				
F_{bru}, ksi:						
(e/D = 1.5)	167	174				
(e/D = 2.0)	250	261				
F_{bry}, ksi:						
(e/D = 1.5)	133	139				
(e/D = 2.0)	190	198				
e, per cent:						
In 2 in.	10[a]	--	10	10	--	
In 4 D	--	--	--	--	10	
E, 10^6 psi	15.5					
E_c, 10^6 psi	15.5					
G, 10^6 psi	5.9					
μ	0.32					
n	--					
ω, lb/in.^{3}	0.162					

Values in parentheses () are tentative values.

[a] Thickness 0.025 inch and over.

[b] Proposed specification values for F_{tu}, F_{ty}, and e.

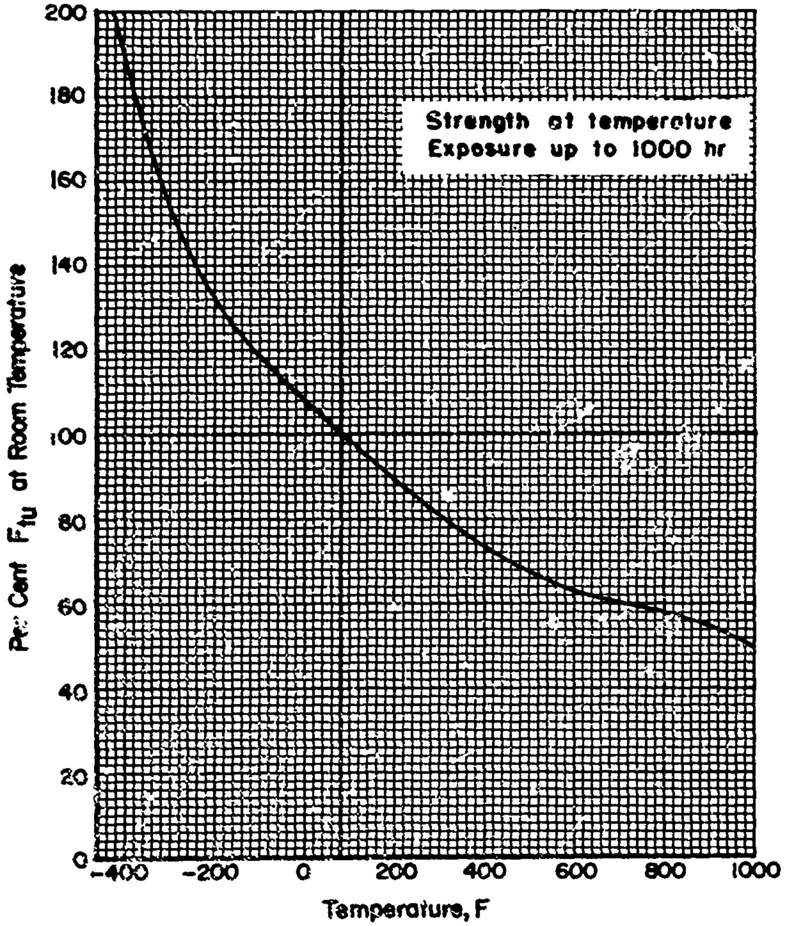

FIGURE 5-2.2.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF ANNEALED Ti-5Al-2.5Sn ALLOY SHEET; TENTATIVE FOR PLATE, BARS, AND FORGINGS

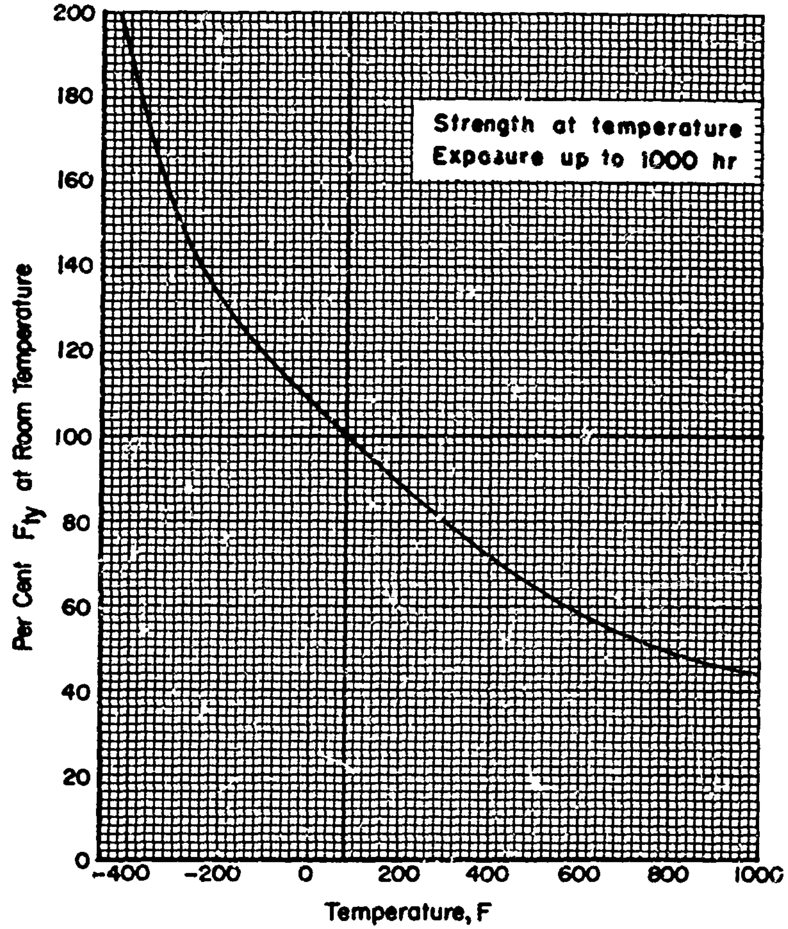

FIGURE 5-2.2.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF ANNEALED Ti-5Al-2.5Sn ALLOY SHEET; TENTATIVE FOR PLATE, BARS, AND FORGINGS

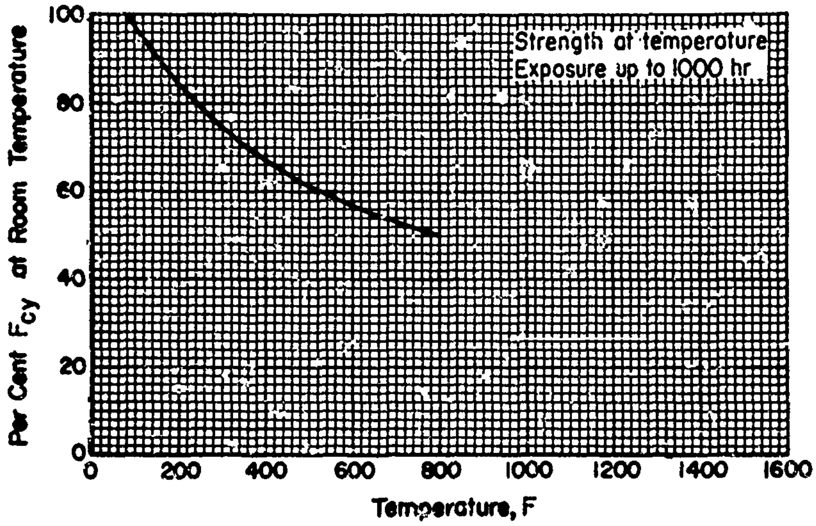

FIGURE 5-2.2.1-3. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF ANNEALED Ti-5Al-2.5Sn ALLOY SHEET; TENTATIVE FOR PLATE, BARS, AND FORGINGS

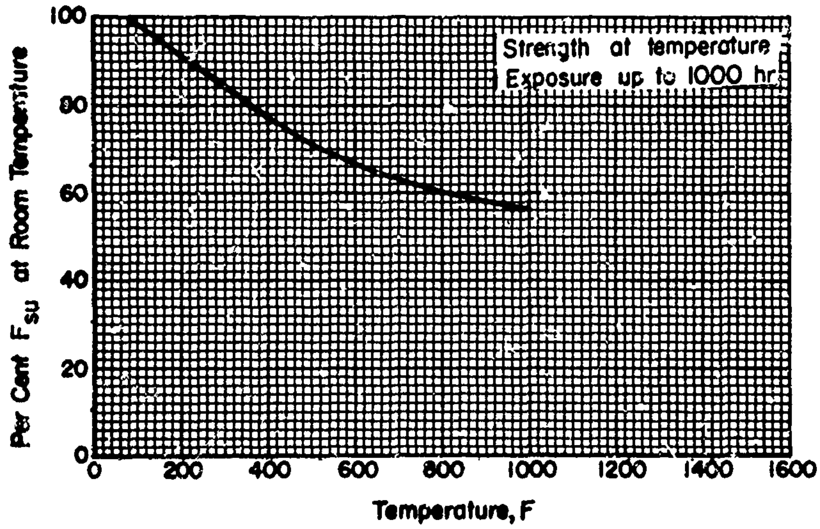

FIGURE 5-2.2.1-4. EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF ANNEALED Ti-5Al-2.5Sn ALLOY SHEET; TENTATIVE FOR PLATE, BARS, AND FORGINGS

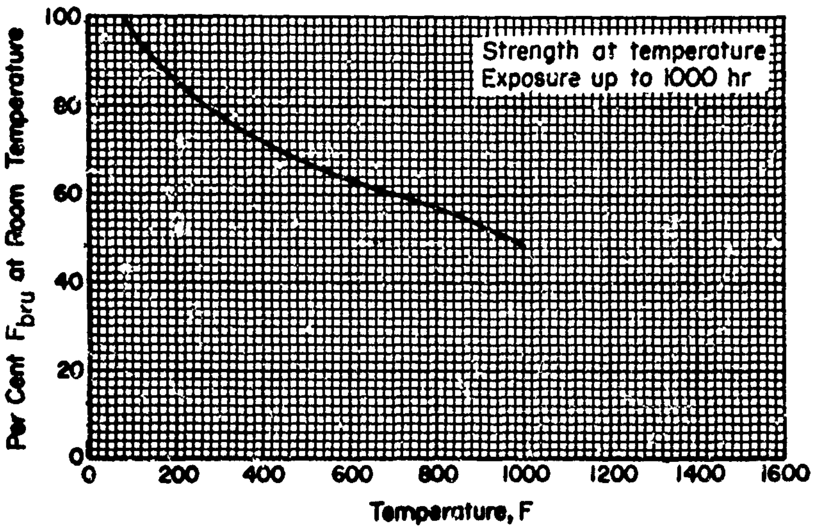

FIGURE 5-2.2.1-5. EFFECT OF TEMPERATURE ON THE ULTIMATE BEARING STRENGTH (F_{bru}) OF ANNEALED Ti-5Al-2.5Sn ALLOY SHEET; TENTATIVE FOR PLATE, BARS, AND FORGINGS

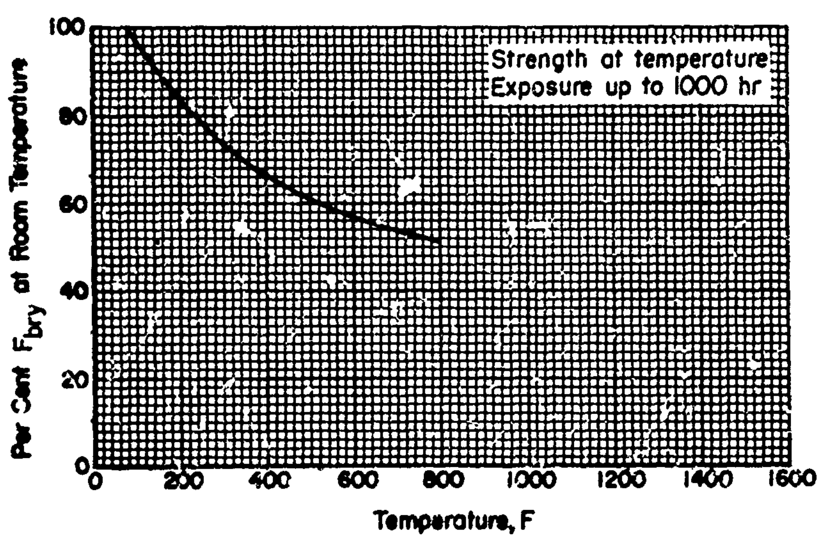

FIGURE 5-2.2.1-6. EFFECT OF TEMPERATURE ON THE BEARING YIELD STRENGTH (F_{bry}) OF ANNEALED Ti-5Al-2.5Sn ALLOY SHEET; TENTATIVE FOR PLATE, BARS, AND FORGINGS

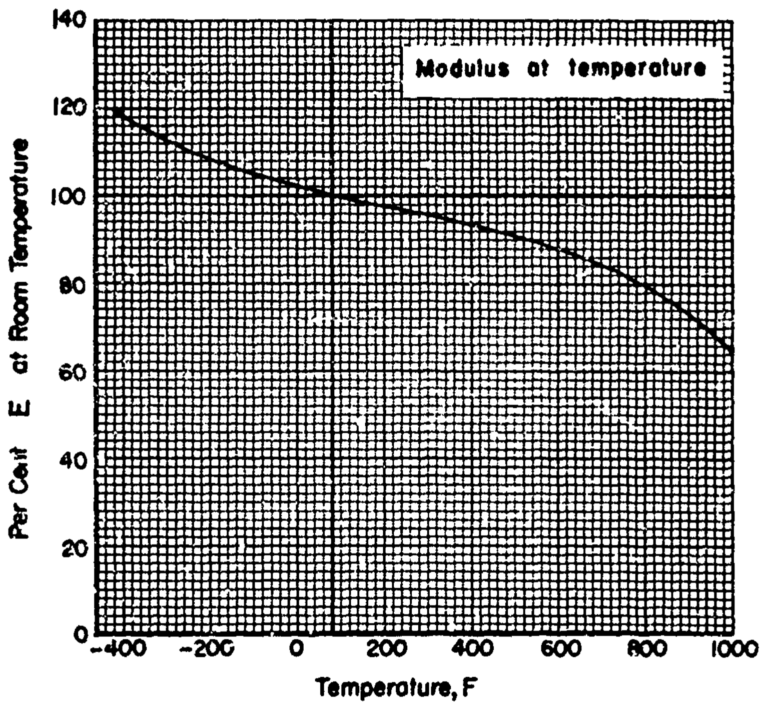

FIGURE 5-2.2.1-7. EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E AND E_c) OF ANNEALED Ti-5Al-2.5Sn ALLOY SHEET; TENTATIVE FOR PLATE, BARS, AND FORGINGS

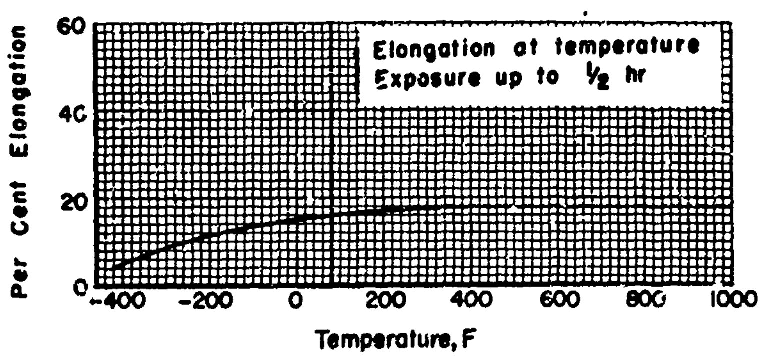

FIGURE 5-2.2.1-8. EFFECT OF TEMPERATURE ON THE ELONGATION OF ANNEALED Ti-5Al-2.5Sn ALLOY SHEET; TENTATIVE FOR PLATE, BARS, AND FORGINGS

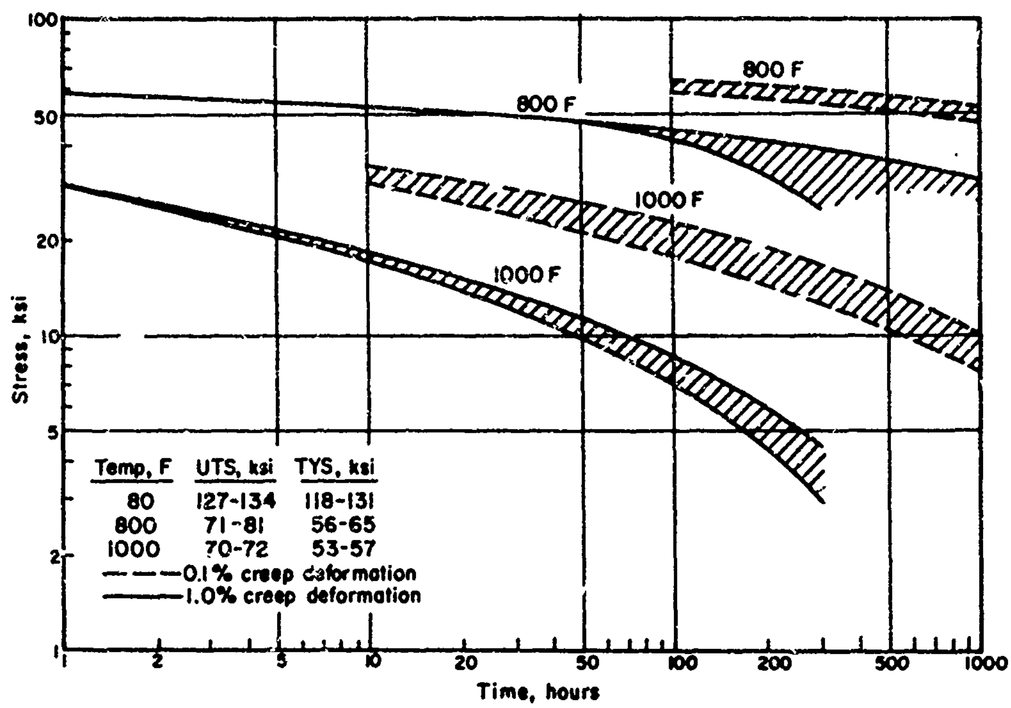

FIGURE 5-2.2.4-1. TYPICAL CREEP PROPERTIES OF ANNEALED Ti-5Al-2.5Sn ALLOY SHEET AT 800 AND 1000 F(16)

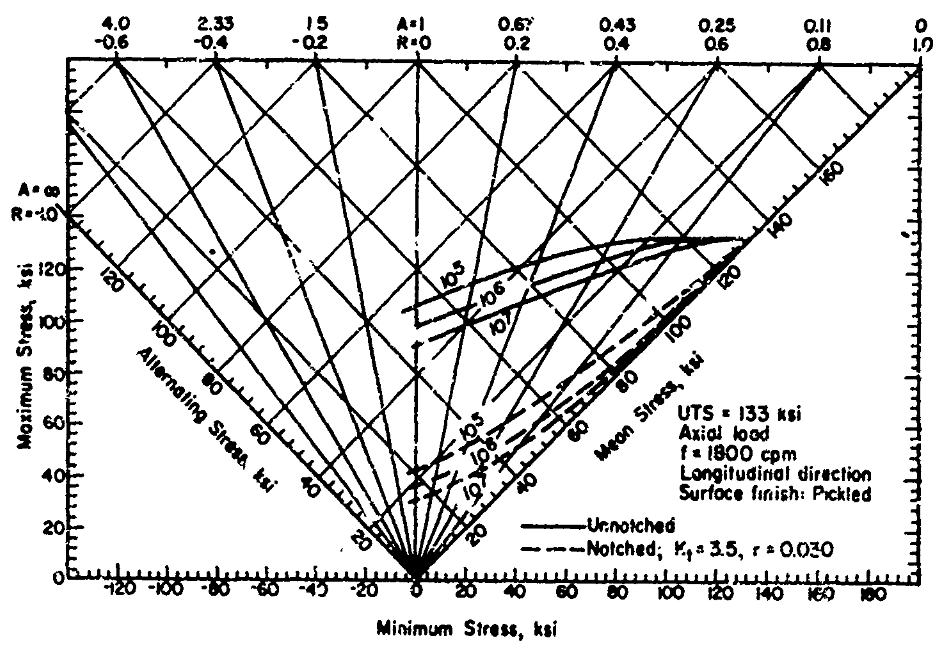

FIGURE 5-2.2.5-1. PARTIAL CONSTANT-LIFE FATIGUE DIAGRAM FOR MILL-ANNEALED Ti-5Al-2.5Sn ALLOY SHEET AT ROOM TEMPERATURE(46)

Note: This figure not included in MIL-HDBK-5.

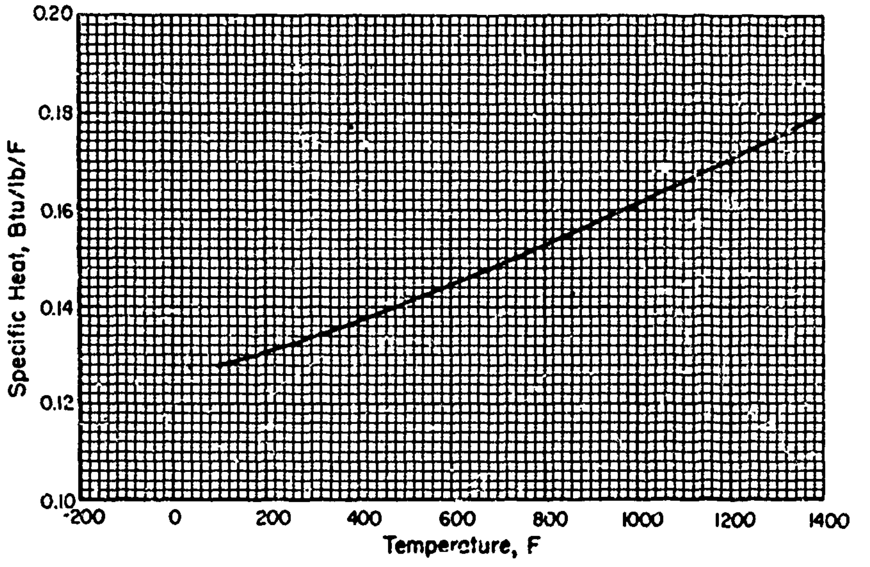

FIGURE 5-2.4-1. EFFECT OF TEMPERATURE ON THE SPECIFIC HEAT (C) OF Ti-5Al-2.5Sn(2)

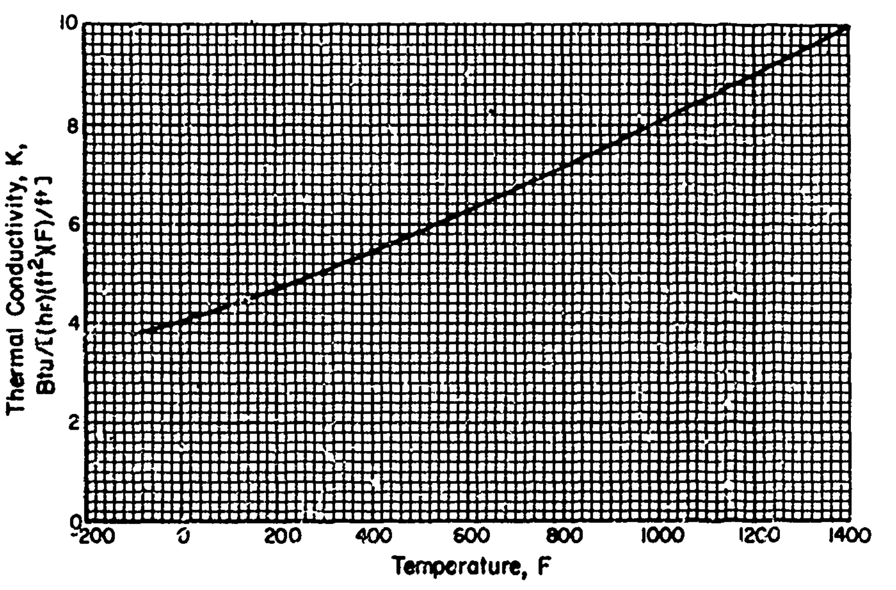

FIGURE 5-2.4-2. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY (K) OF Ti-5Al-2.5Sn(2)

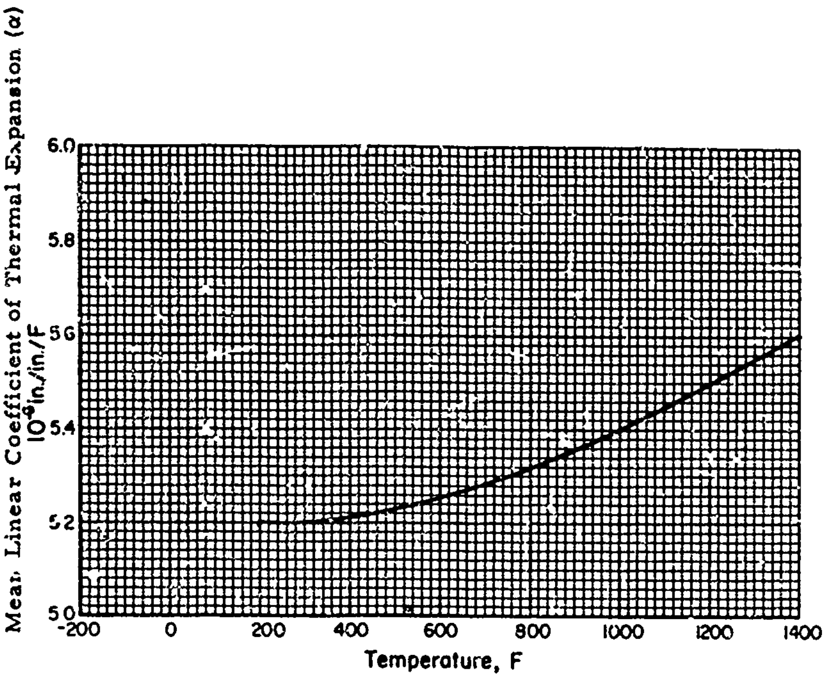

FIGURE 5-2.4-3. MEAN LINEAR COEFFICIENT OF THERMAL EXPANSION (α) OF Ti-5Al-2.5Sn BETWEEN ROOM TEMPERATURE AND INDICATED TEMPERATURE(2)

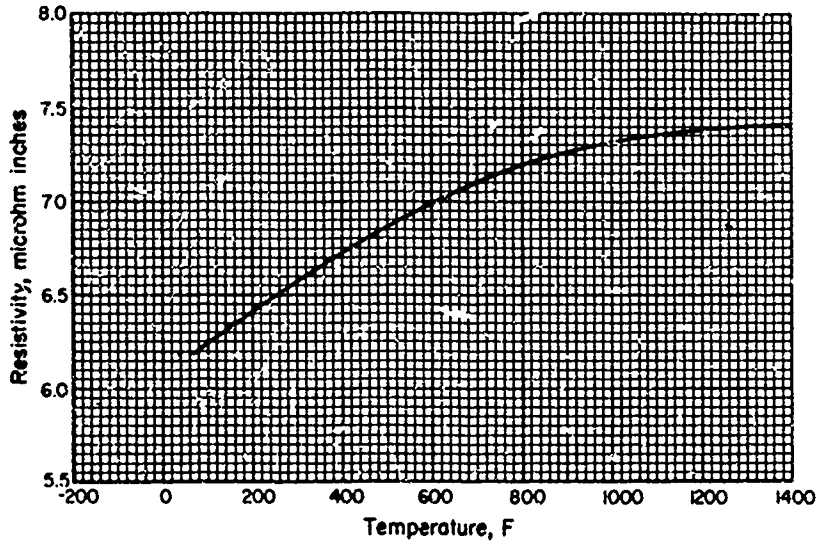

FIGURE 5-2.4-4. EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY (ρ) OF Ti-5Al-2.5Sn(2)

5-3 Titanium Alloy Ti-8Al-Mo-IV

5-3.0 SPECIFICATIONS AND FORMS

This section covers titanium alloy Ti-8Al-1Mo-1V of the following specifications and forms:

Specification	Form
MIL-T-9046	Sheet, strip, and plate
---	Extrusions
MIL-H-81200	Heat treatment, all forms

At the present time, a variety of modified and developmental heat treatments are being investigated in order to obtain improved fracture resistance in this alloy. The following heat treatments are of special interest:

Designation	Description of Heat Treatment
Full anneal (S,P)*	1430 to 1470 F/8 hr (MIL-H-81200)
Full anneal (B,F)	1650 to 1850 F/1 hr/WQ or AC + 1050 to 1100 F/8 hr/AC (MIL-H-81200)
Single anneal (S,P)	1435 to 1465 F/1 to 8 hr/FC to 700 F (MIL-H-81200)
Duplex anneal (S,P)	1435 to 1465 F/1 to 8 hr/FC to 700 F + 1435 to 1465 F/1/4 to 1 hr/AC (MIL-H-81200)
Duplex anneal (B,F)	1650 to 1850 F/3/4 to 1 1/4 hr/WQ or AC + 1000 to 1125 F/8 to 24 hr/AC (MIL-H-81200)
Modified duplex anneal (B,F), (minimum distortion)	1650 to 1675 F/50 to 65 min./WQ or AC + 1100 to 1125 F/7 to 9 hr/AC (MIL-H-81200)
Modified duplex anneal (B,F) (max. creep resistance)	1825 to 1850 F/50 to 65 min./WQ or AC + 1100 to 1125 F/7 to 9 hr/AC (MIL-H-81200)

Several of the heat treatments listed above are being employed for extrusions, depending on section size.

5-3.1 ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES

Table 5-3.1-1 summarizes the design mechanical properties of mill-annealed Ti-8Al-1Mo-1V alloy. Duplex-annealed properties are summarized in Table 5-3.1-2.

5-3.2 ENVIRONMENTAL EFFECTS FOR MILL-ANNEALED MATERIAL

5-3.2.1 Elevated-Temperature Effects

Effect of temperature data are presented in Figures 5-3.2.1-1 and 5-3.2.1-2.

5-3.2.3 Stress-Strain and Tangent Modulus Curves

Typical tensile and compressive stress-strain curves for room and elevated temperatures are presented in Figures 5-3.2.3-1 through 5-3.2.3-4. Typical compressive tangent-modulus curves are presented in Figures 5-3.2.3-5 and 5-3.2.3-6.

5-3.2.5 Fatigue Effects

An S-N diagram for fatigue behavior is presented in Figure 5-3.2.5-1.

5-3.2.6 Residual Strength Data

Residual-strength data are presented in Figure 5-3.2.6-1.

5-3.3 ENVIRONMENTAL EFFECTS FOR DUPLEX-ANNEALED MATERIAL

5-3.3.1 Elevated Temperature Effects

Effect of temperature data are presented in Figures 5-3.3.1-1 through 5-3.3.1-7.

5-3.3.3 Stress-Strain and Tangent Modulus Curves

Typical tensile and compressive stress-strain curves for room and elevated temperatures are presented in Figures 5-3.3.3-1 through 5-3.3.3-4. Typical compressive tangent modulus curves are presented in Figures 5-3.3.3-5 through 5-3.3.3-6.

5-3.3.5 Fatigue Effects

Constant life diagrams for fatigue behavior are presented in Figures 5-3.3.5-1 through 5-3.3.5-6. Data from exposed and unexposed specimens have been utilized. Data for 5000 hour, 25 ksi stressed exposure at 400 F and 650 F have been included. These data are not applicable beyond the environmental limits indicated.

Figures 5-3.3.5-7 and 5-3.3.5-8 present S-N diagrams for high notch factors.

5-3.3.6 Residual Strength Data

Residual strength data are presented in Figures 5-3.3.6-1 and 5-3.3.6-2.

5-3.4 Thermophysical Effects

The effect of temperature on physical properties is displayed in Figures 5-3.4-2 through 5-3.4-4.

*Product forms designated by S (sheet), P (plate), B (bar), F (forging), and E (extrusion).

TABLE 5-3.1-1. ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES OF SINGLE ANNEALED Ti-8Al-1Mo-1V

Alloy	MIL-T-9046 Type II Composition F							
Form	Sheet and strip			Plate				Extrusions
Condition	Single annealed (S,P)							
Thickness or diameter, in.	<0.020	0.020 to 0.187		0.188 to 0.500	0.501 to 1.000	1.001 to 2.500	2.501 to 4.000	≤0.75[d]
Basis	S	A	B	S	S	S	S	S[c]
Mechanical properties:								
F_{tu}, ksi								
L	145	149	154	145	140	130	120	[illegible]
T	145	145	150	145	140	130	120	[illegible]
F_{ty}, ksi								
L	135	138	142	135	130	120	110	[illegible]
T	135	135	139	135	130	120	110	[illegible]
F_{cy}, ksi								
L	143	146	150	143	137	[illegible]	[illegible]	[illegible]
T	143	143	147	143	[illegible]	[illegible]	[illegible]	[illegible]
F_{su}, ksi	91	91	94	(91)	[illegible]	[illegible]	[illegible]	[illegible]
F_{bru}, ksi:								
(e/D = 1.5)	--	--	--	--	--	--	--	--
(e/D = 2.0)	290	290	300	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
F_{bry}, ksi:								
(e/D = 1.5)	--	--	--	--	--	--	--	--
(e/D = 2.0)	216	216	222	[illegible]	[illegible]	[illegible]	(176)	[illegible]
e, per cent:								
In 2 in.	--	[a]10	--	10	10	10	8	[illegible]
In 4 D	--	--	--	--	--	--	--	[illegible]
E, 10^6 psi	17.5[b]							
E_c, 10^6 psi	18.0[b]							
G, 10^6 psi	6.7							
μ	0.32							
α	-							
ω, lb/in.^{3}	0.158							

Values in parentheses () are tentative values.

[a]Thickness ≥ 0.025 inch and over. [b]May vary with grain direction. [c]Proposed specification values for F_{tu}, F_{ty}, and e. [d]Diameter of maximum inscribed circle.

TABLE 5-3:1-2 [illegible]

Alloy	MIL-T-9046 Type II Composition F					
Form	Sheet and strip			Plate		
Condition	Duplex annealed (S,P)					
Thickness or diameter, in.	<0.020	0.020 to 0.167		0.188 to 1.000	1.001 to 2.000	2.001 to 4.000
Basis	S	A	B	S	S	S
Mechanical properties:						
F_{tu}, ksi						
L	130	133	137	130	125	120
T	130	130	[illegible]	130	125	120
F_{ty}, ksi						
L	120	121	124	120	115	110
T	120	120	123	120	115	110
F_{cy}, ksi						
L	127	128	131	127	[illegible]	117
T	127	127	130	127	[illegible]	117
F_{su}, ksi	82	82	84	([illegible])	([illegible])	(76)
F_{bru}, ksi:						
(e/D = 1.5)	--	--	--	--	--	--
(e/D = 2.0)	260	260	[illegible]	([illegible])	(250)	(240)
F_{bry}, ksi:						
(e/D = 1.5)	--	--	--	--	--	--
(e/D = 2.0)	192	192	[illegible]	([illegible])	([illegible])	(176)
e, per cent:						
In 2 in.	--	10[a]	--	10	10	8
In 4 D	--	--	--	--	--	--
E, 10^6 psi	17.5[b]					
E_c, 10^6 psi	18.0[b]					
G, 10^6 psi	6.7					
μ	0.32					
n	-					
ω, lb/in.^{3}	0.158					

Values in parentheses () are tentative values

[a]Thickness 0.025 inch and over.

[b]May vary with grain direction.

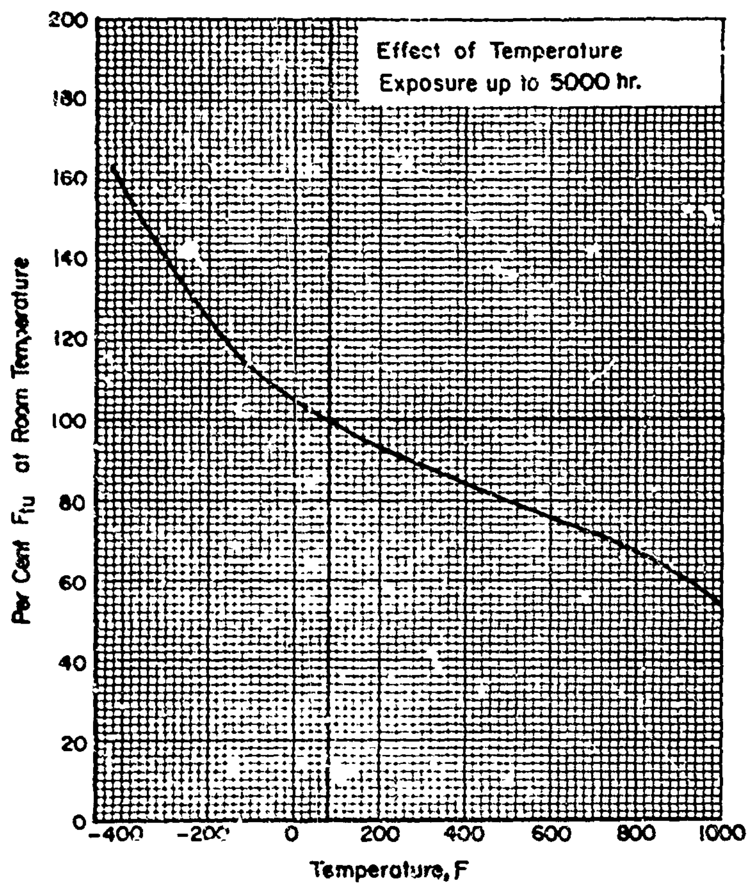

FIGURE 5-3.2.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF MILL-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET

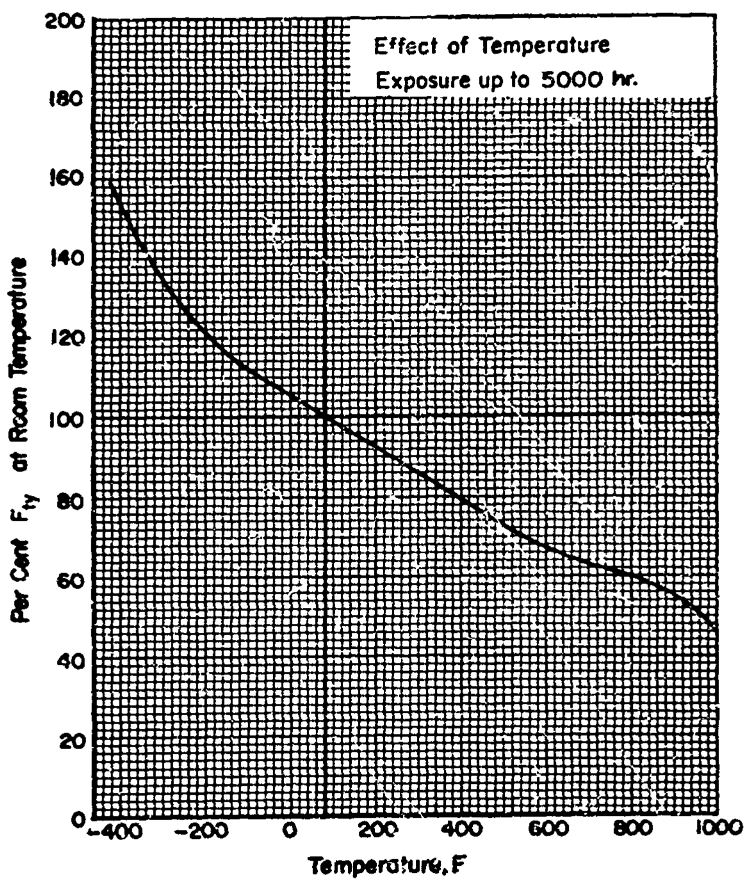

FIGURE 5-3.2.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF MILL-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET

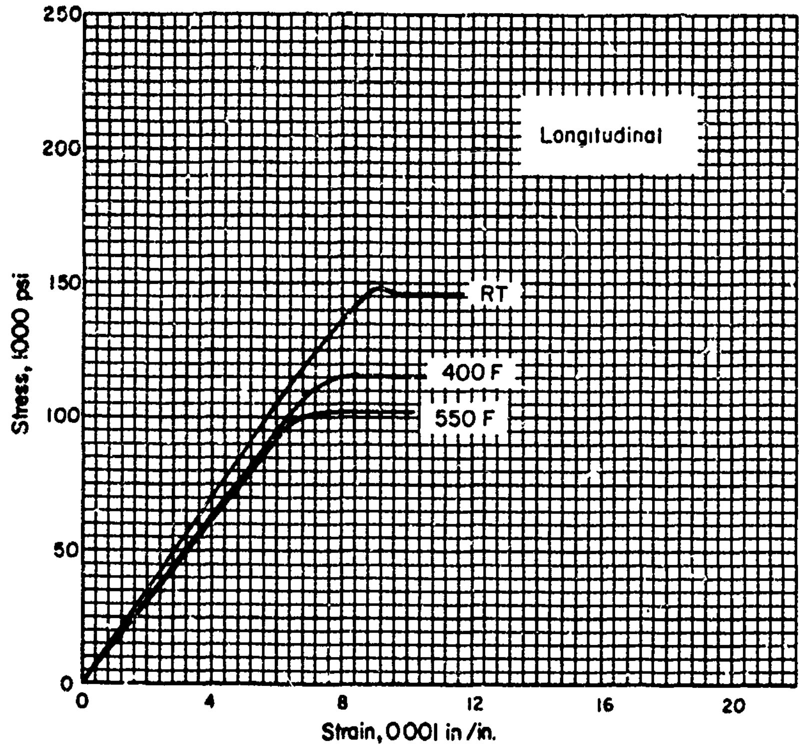

FIGURE 5-3.2.3-1. TYPICAL TENSILE STRESS-STRAIN CURVES FOR MILL-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

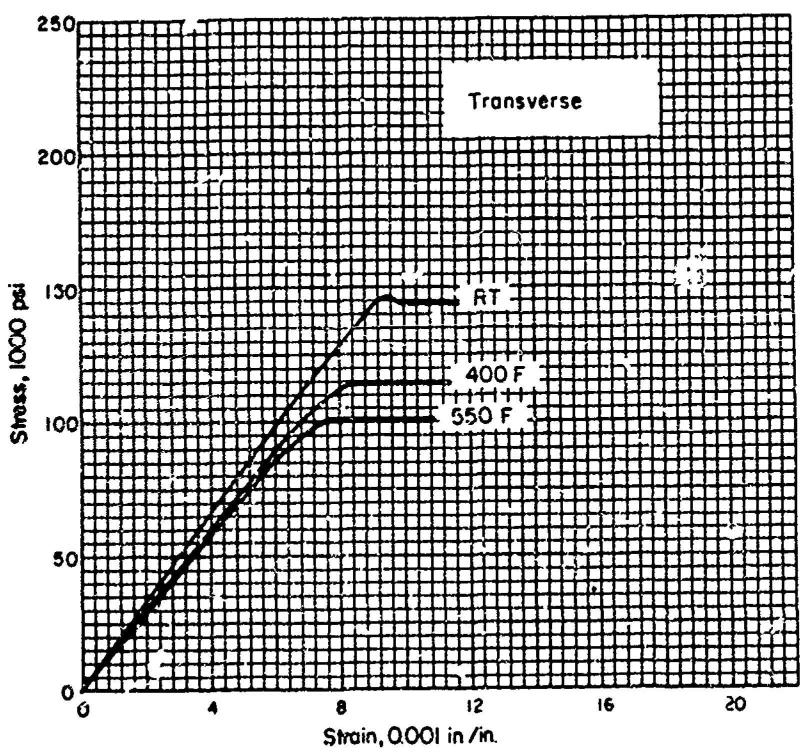

FIGURE 5-3.2.3-2. TYPICAL TENSILE STRESS-STRAIN CURVES FOR MILL-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

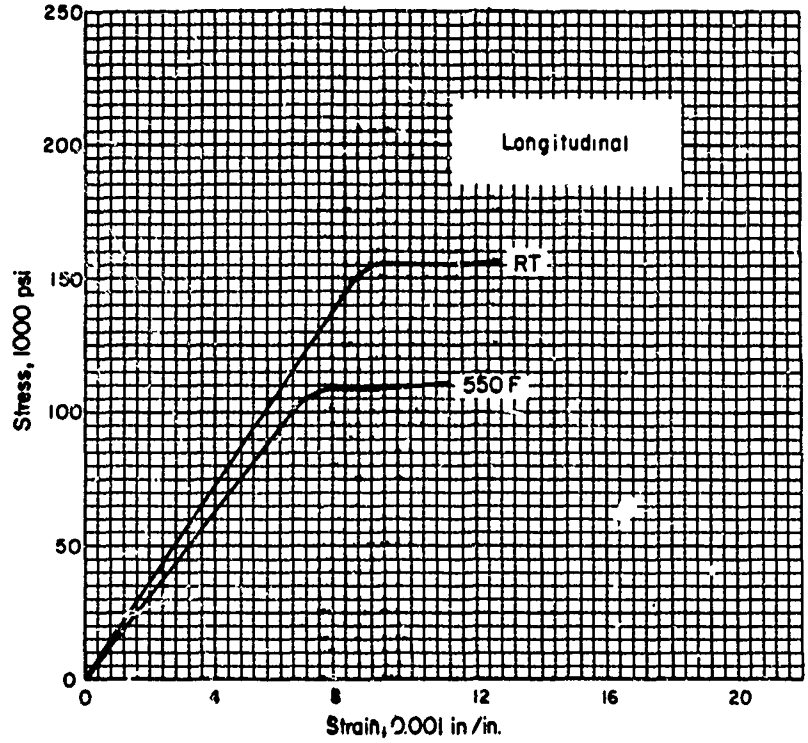

FIGURE 5-3.2.3-3. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR MILL-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

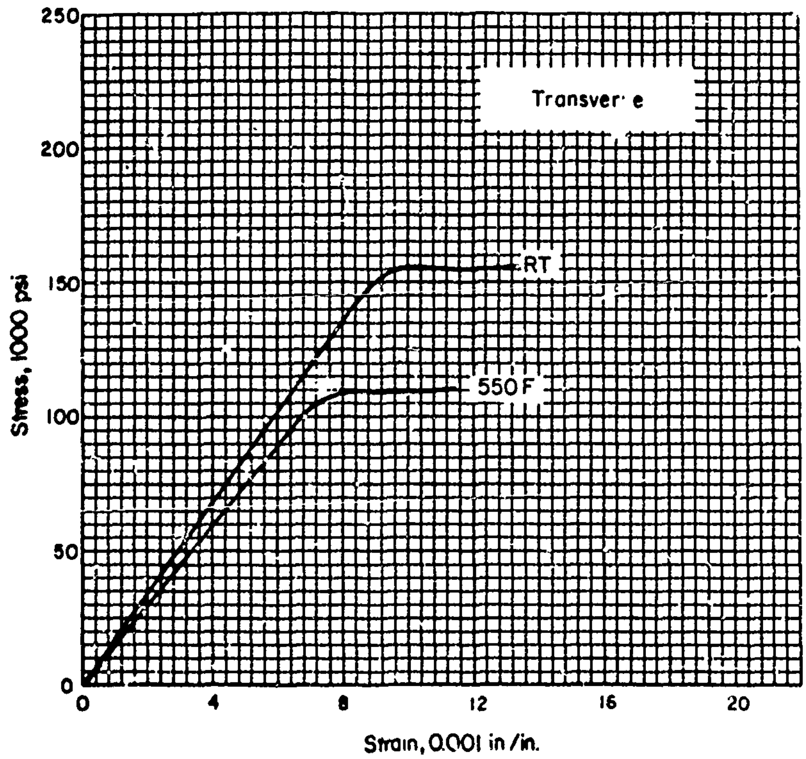

FIGURE 5-3.2.3-4. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR MILL-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

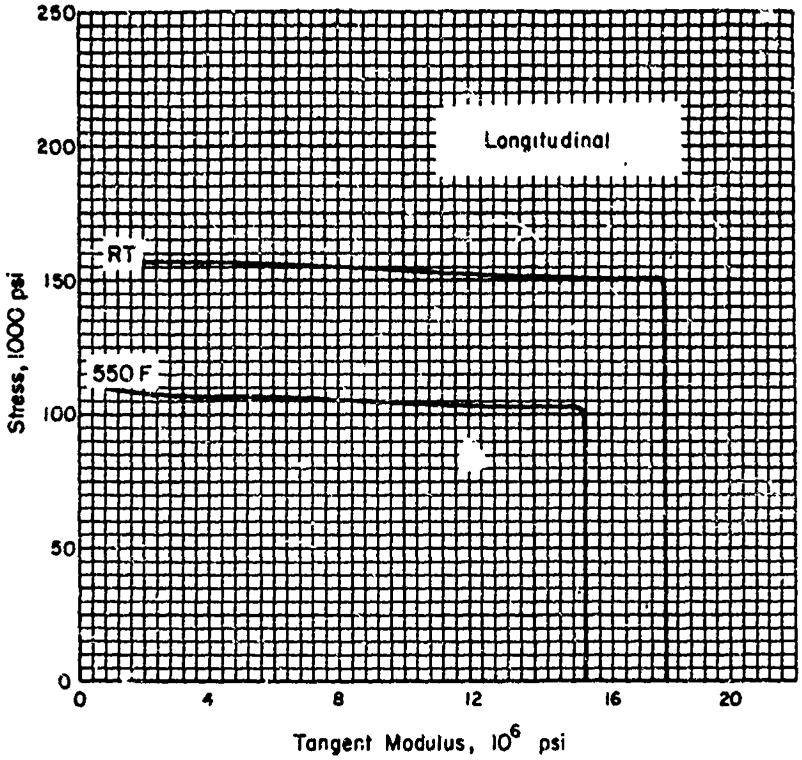

FIGURE 5-3.2.3-5. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR MILL-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

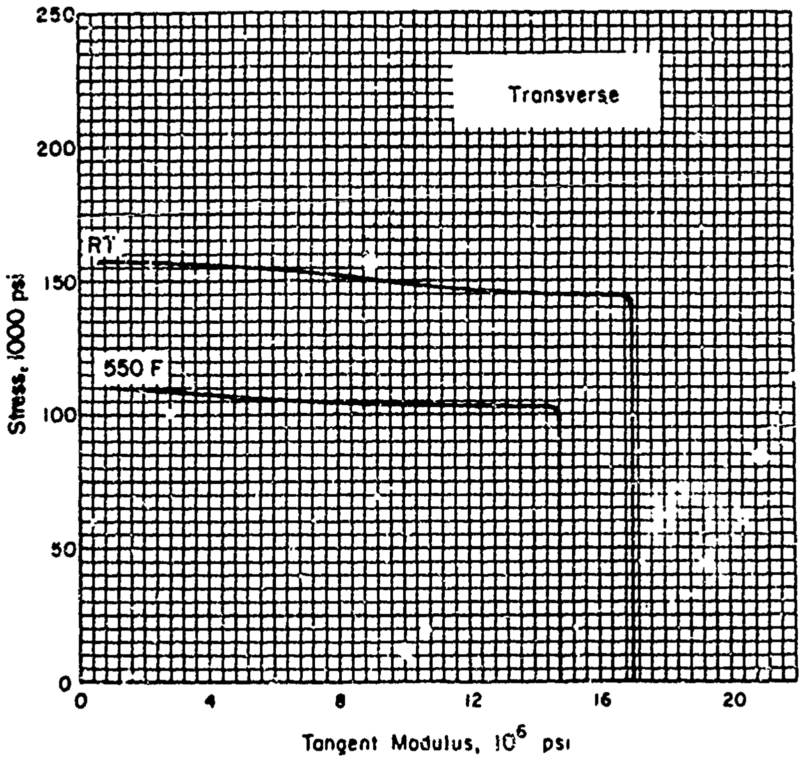

FIGURE 5-3.2.3-6. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR MILL-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

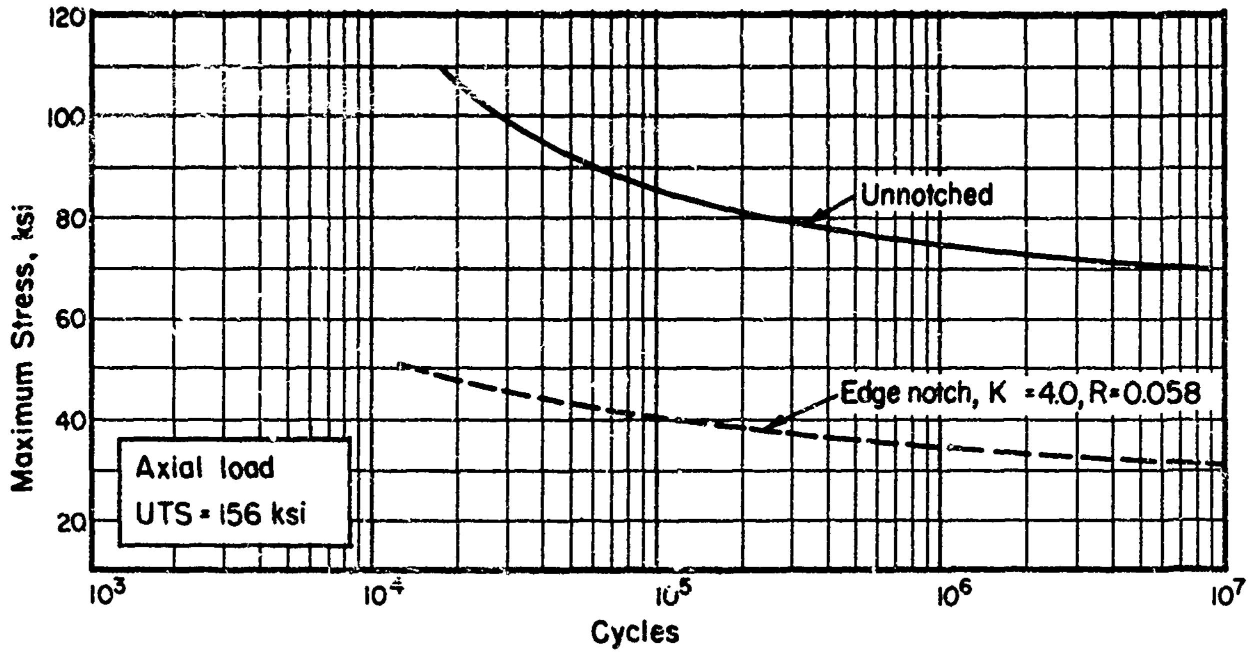

FIGURE 5-3.2.5-1. S-N DIAGRAM FOR MILL-ANNEALED Ti-8Al-1Mo-1V SHEET AT ROOM TEMPERATURE WITH A MEAN STRESS OF 25 KSI(39)

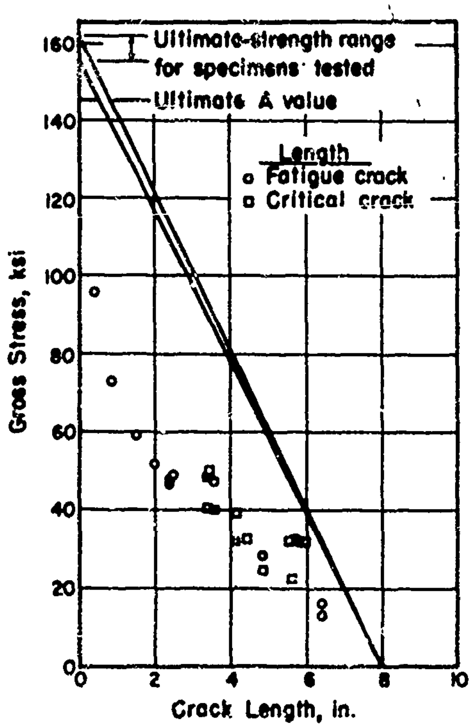

FIGURE 5-3.2.6-1. RESIDUAL STRENGTH DATA FOR 8-INCH-WIDE MILL ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET OF 0.040-INCH NOMINAL THICKNESS(24, 27)

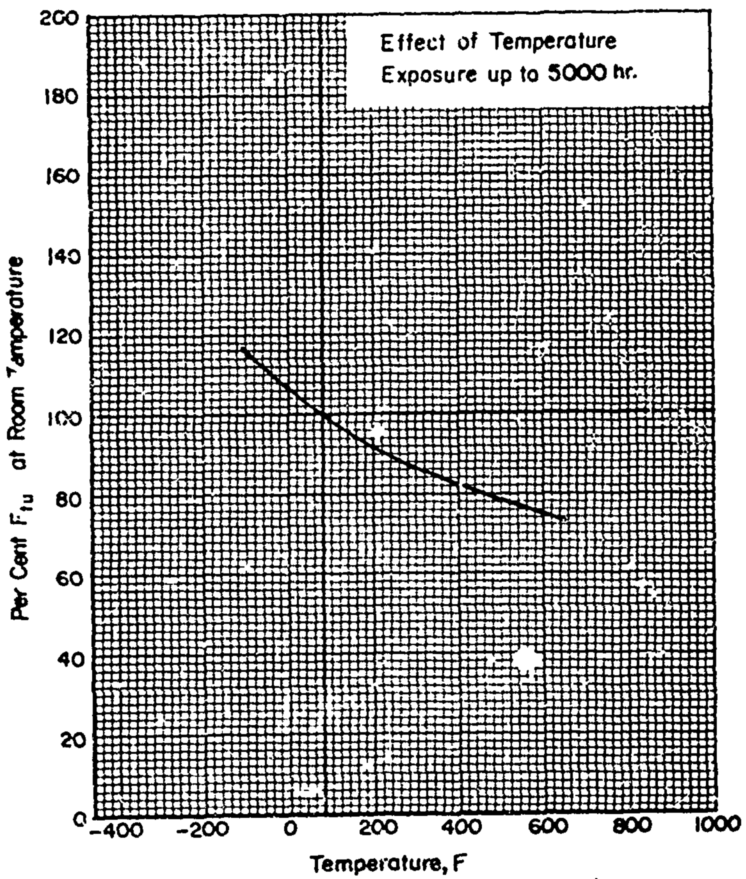

FIGURE 5-3.3.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET

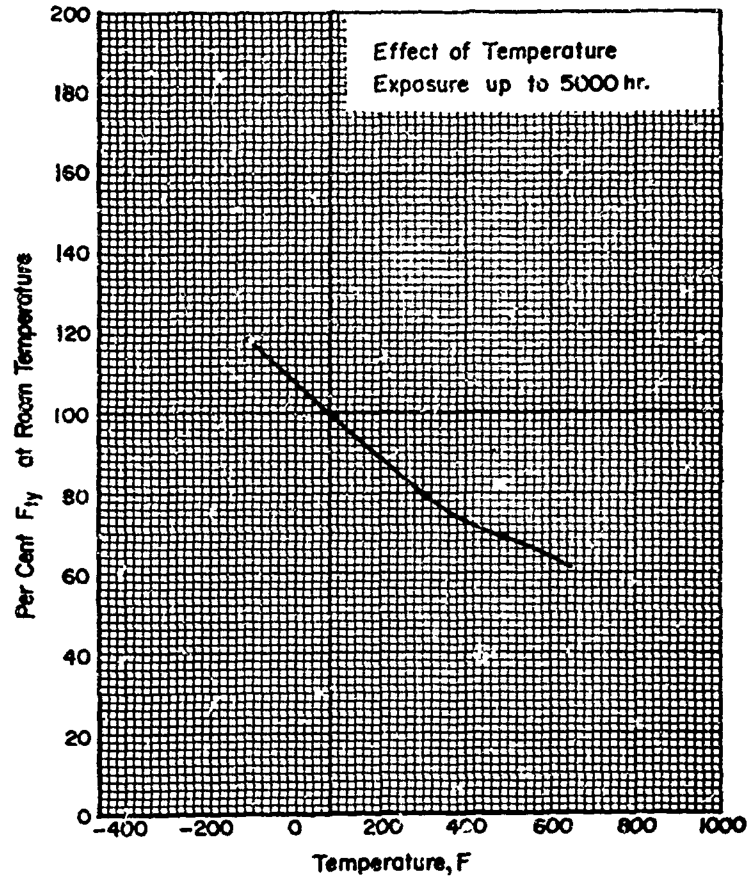

FIGURE 5-3.3.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET

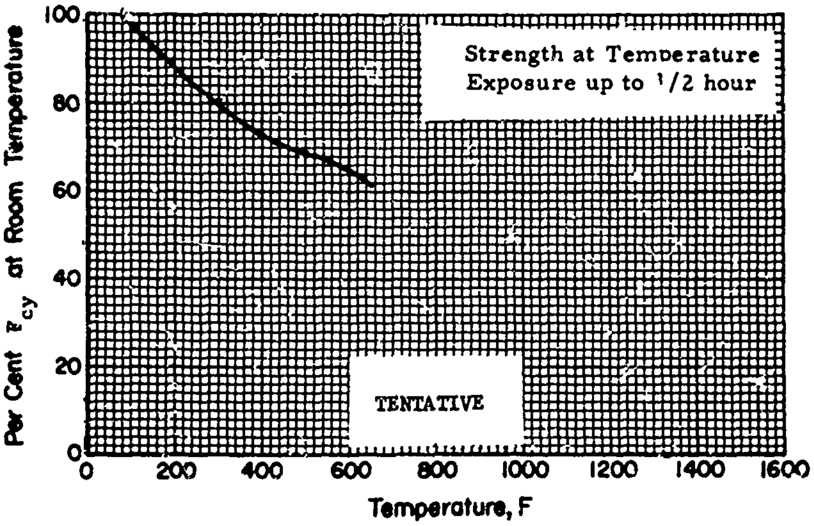

FIGURE 5-3.3.1-3. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET

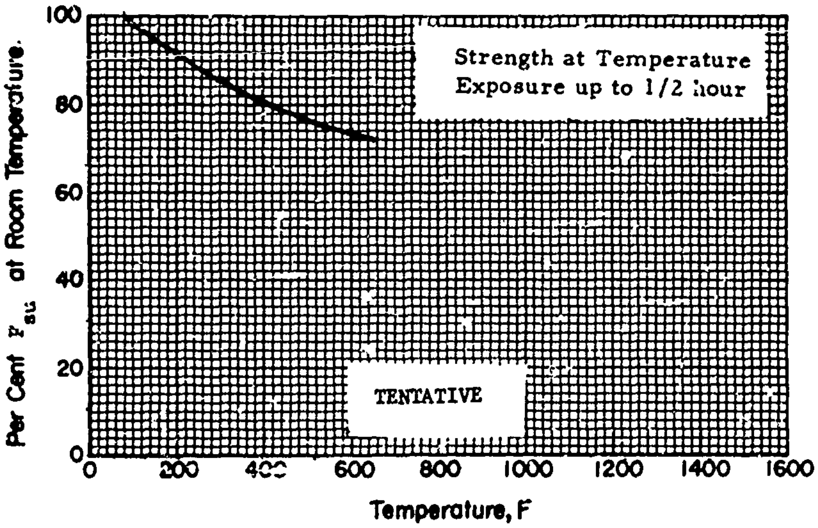

FIGURE 5-3.3.1-4. EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET

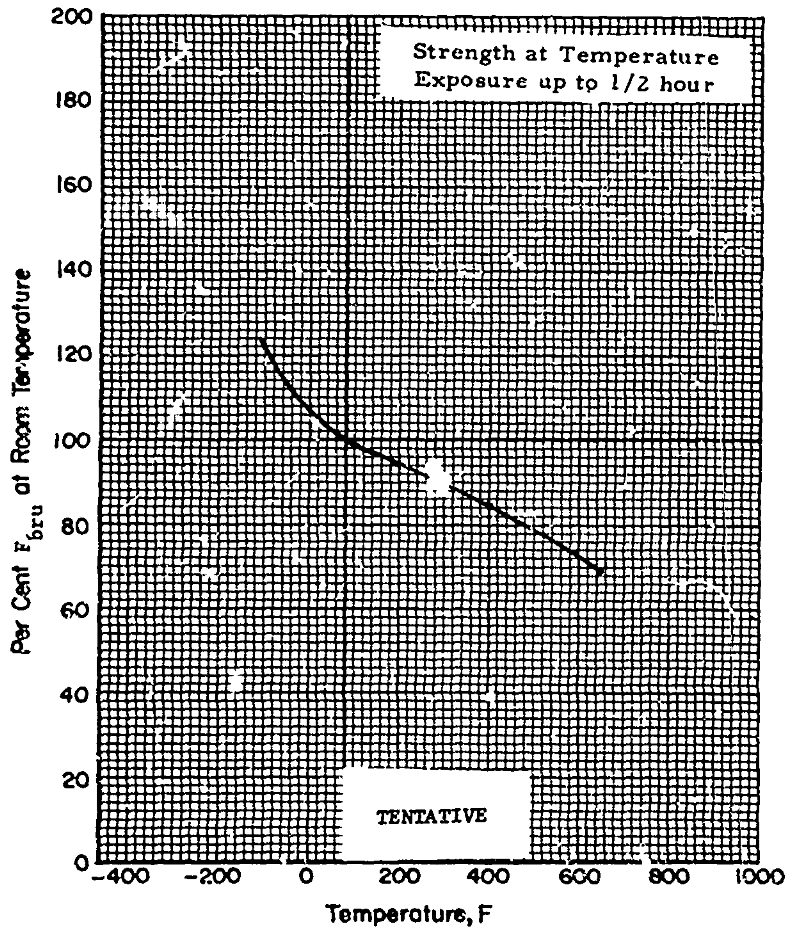

FIGURE 5-3.3.1-5. EFFECT OF TEMPERATURE ON THE ULTIMATE BEARING STRENGTH (F_{bru}) OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET(35,41)

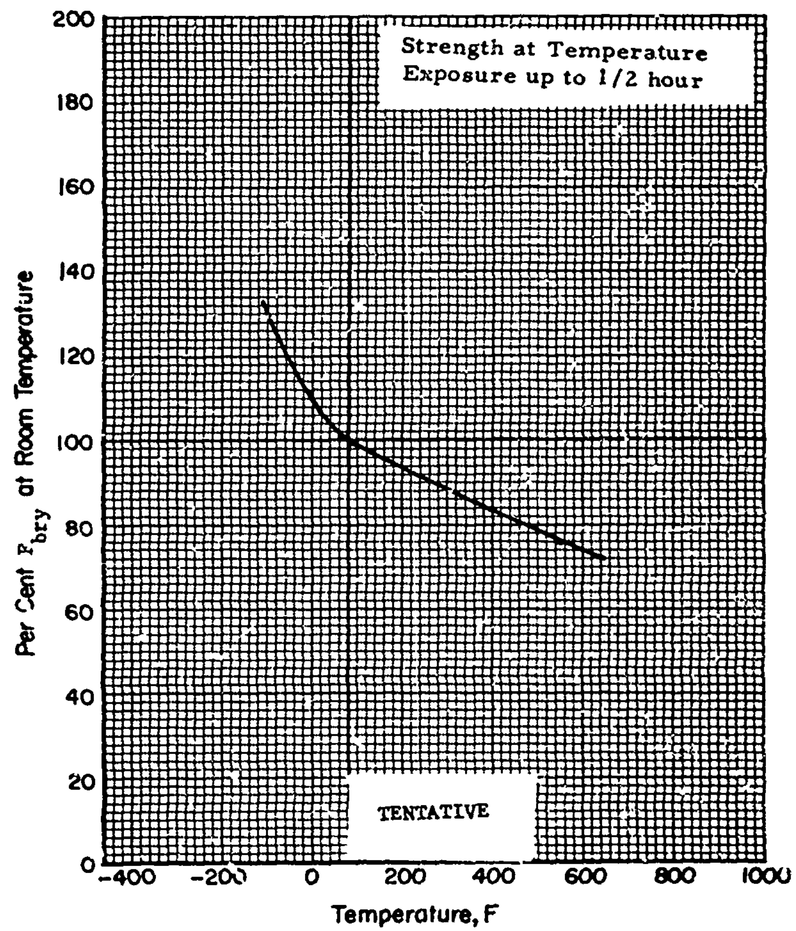

FIGURE 5-3.3.1-6. EFFECT OF TEMPERATURE ON THE BEARING YIELD STRENGTH (F_{bry}) OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET(35,41)

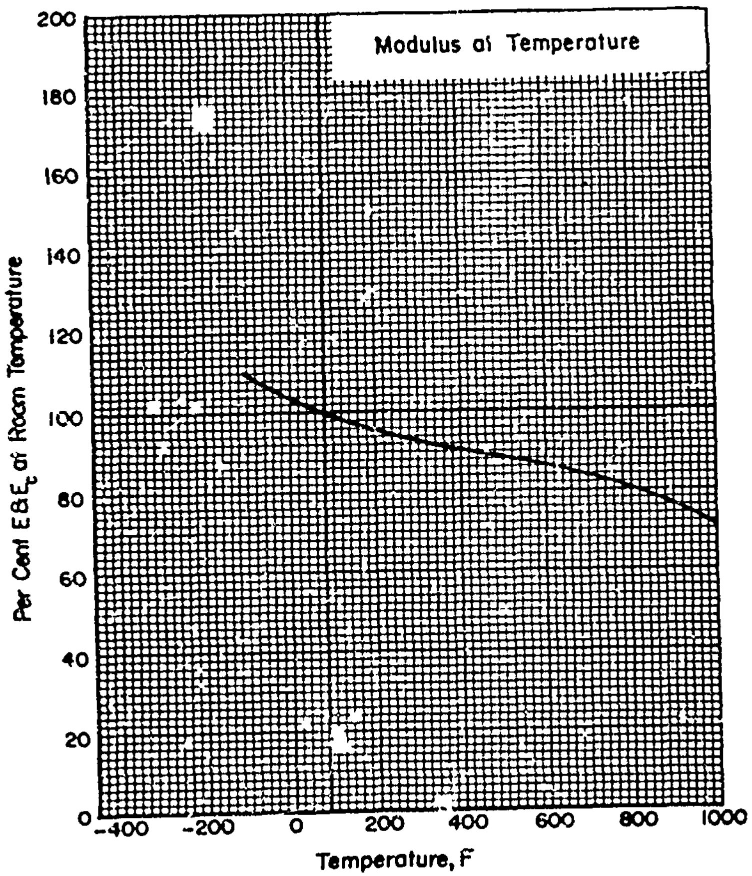

FIGURE 5-3.3.1-7. EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E AND E_c) OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET

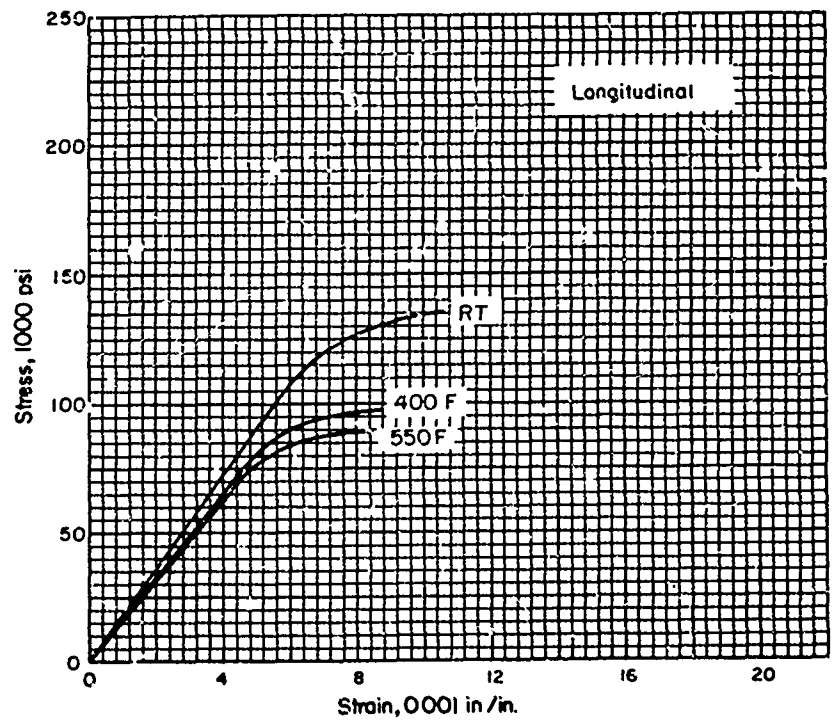

FIGURE 5-3.3.3-1. TYPICAL TENSILE STRESS-STRAIN CURVES FOR DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

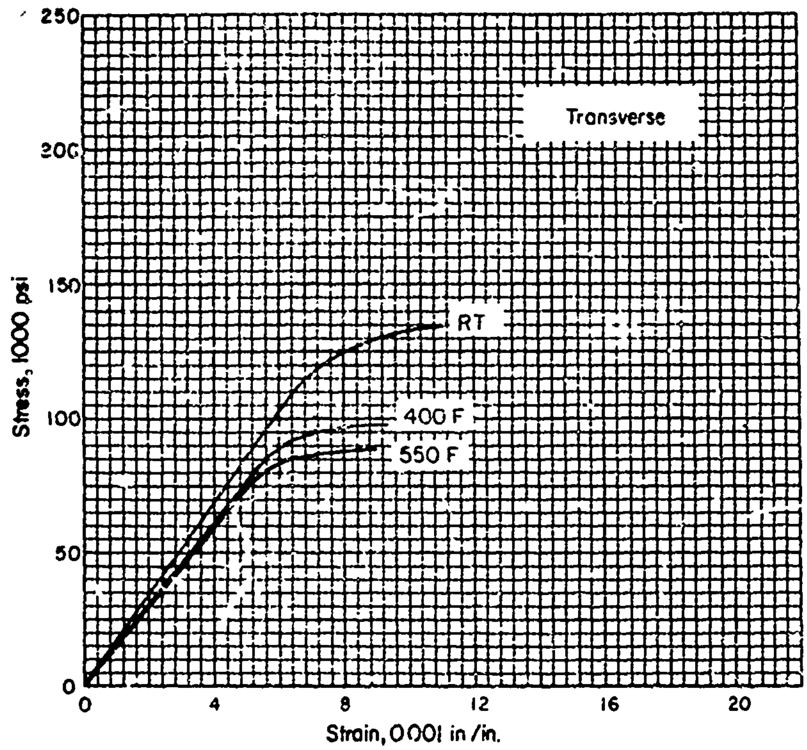

FIGURE 5-3.3.3-2. TYPICAL TENSILE STRESS-STRAIN CURVES FOR DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

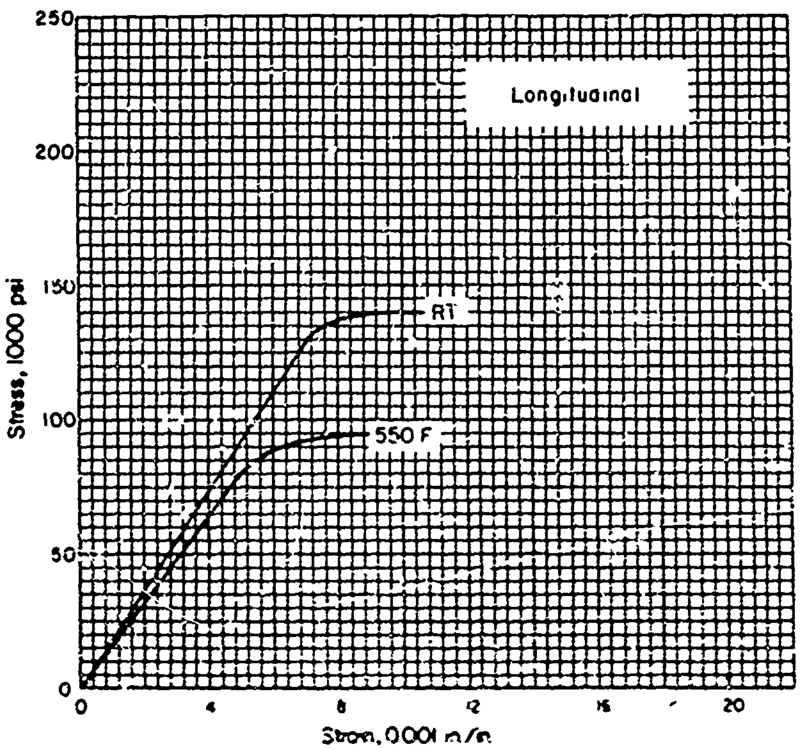

FIGURE 5-3.3.3-3 TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

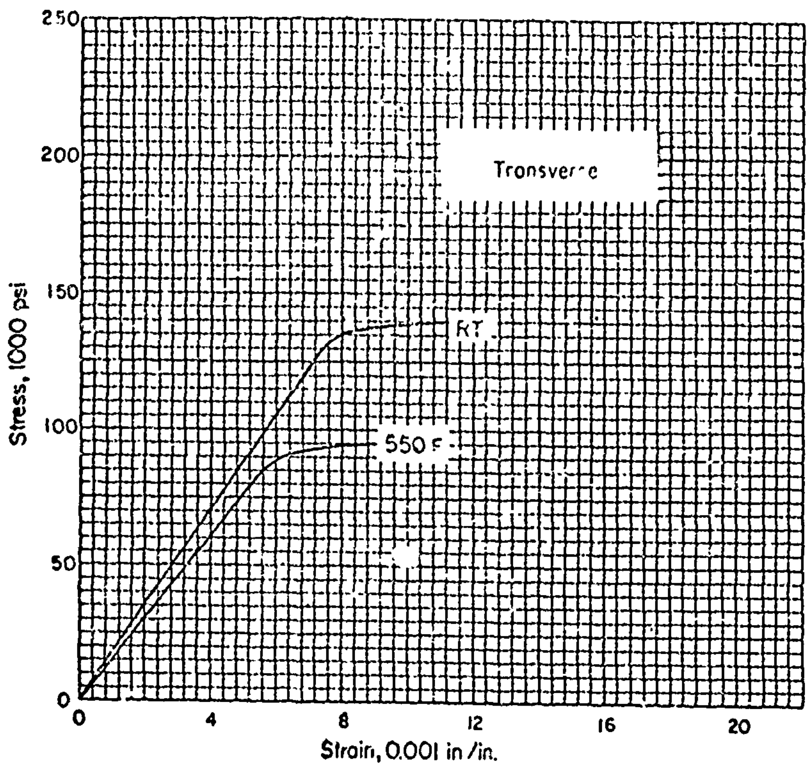

FIGURE 5-3.3.3-4. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

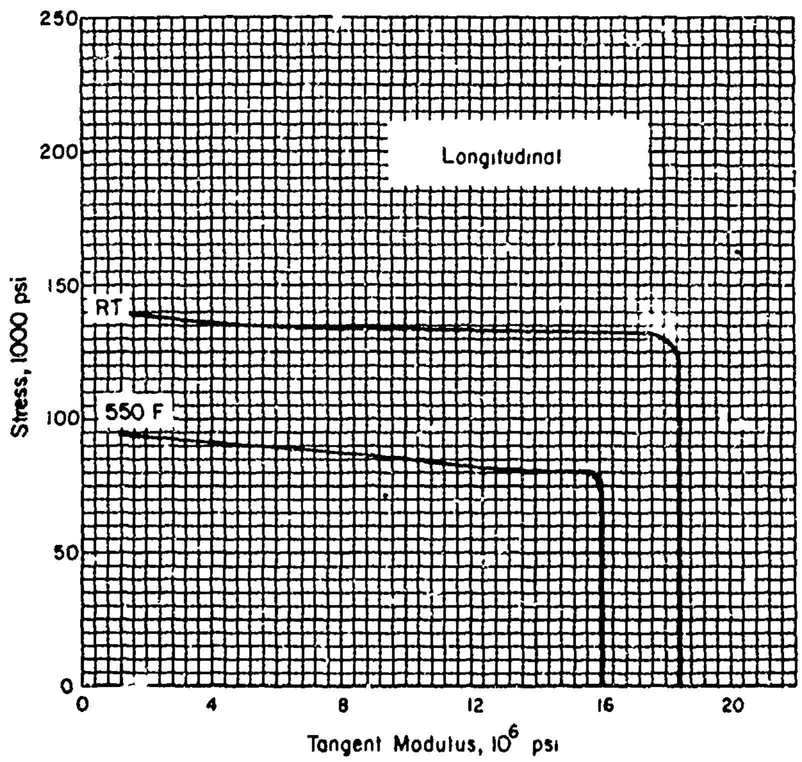

FIGURE 5-3.3.3-5. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

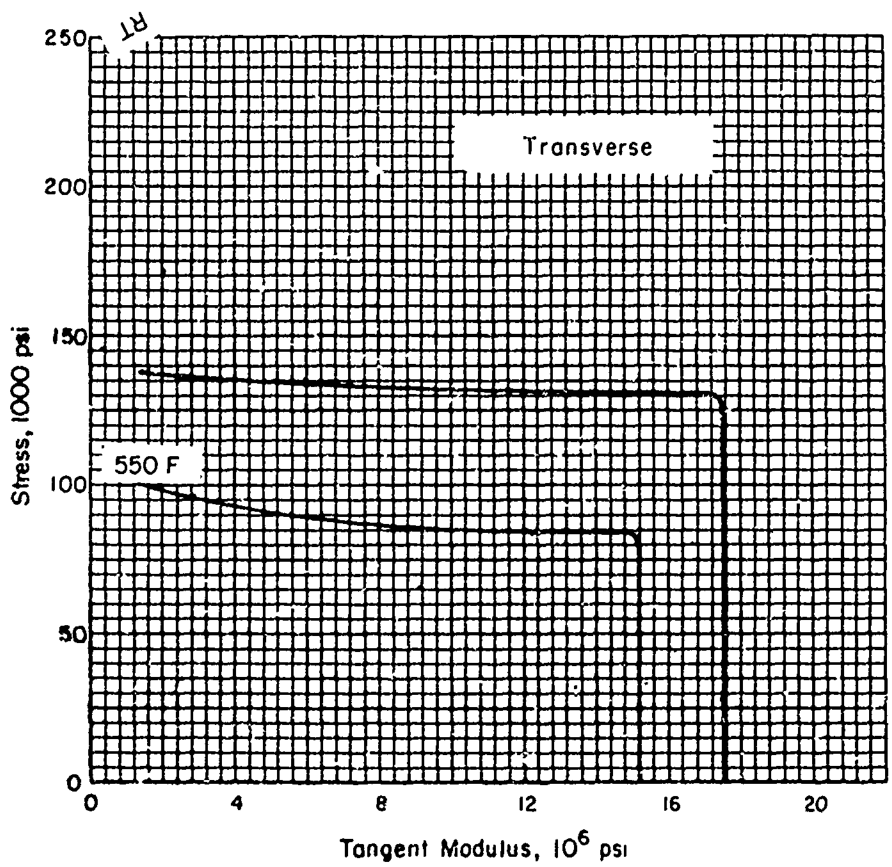

FIGURE 5-3.3.3-6. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

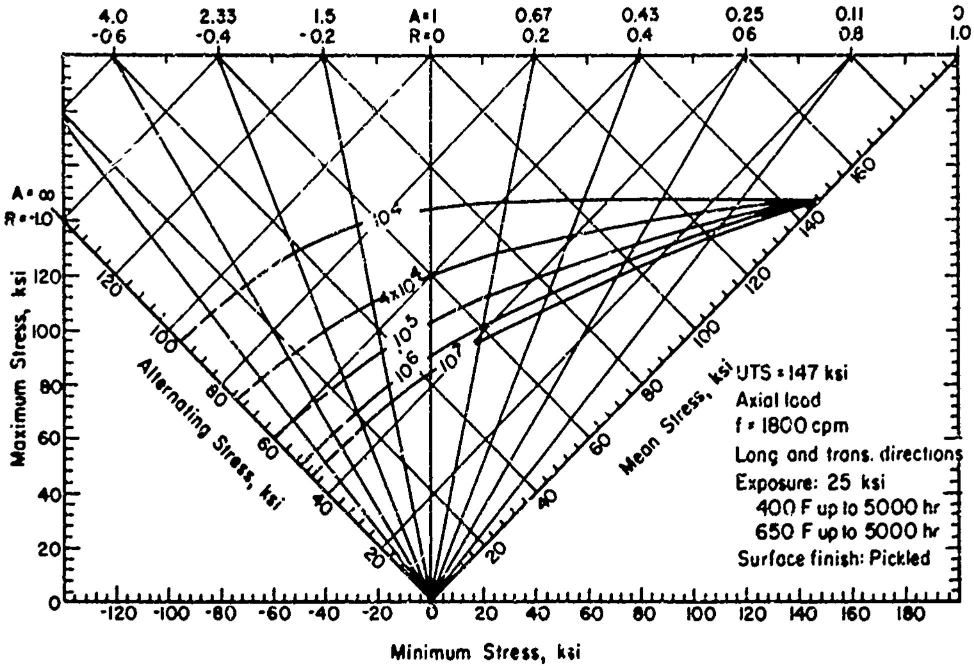

FIGURE 5-3.3.5-1. CONSTANT-LIFE FATIGUE DIAGRAM FOR DUPLEX-ANNEALED, UNNOTCHED, Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM TEMPERATURE IN EXPOSED AND UNEXPOSED CONDITIONS[43]

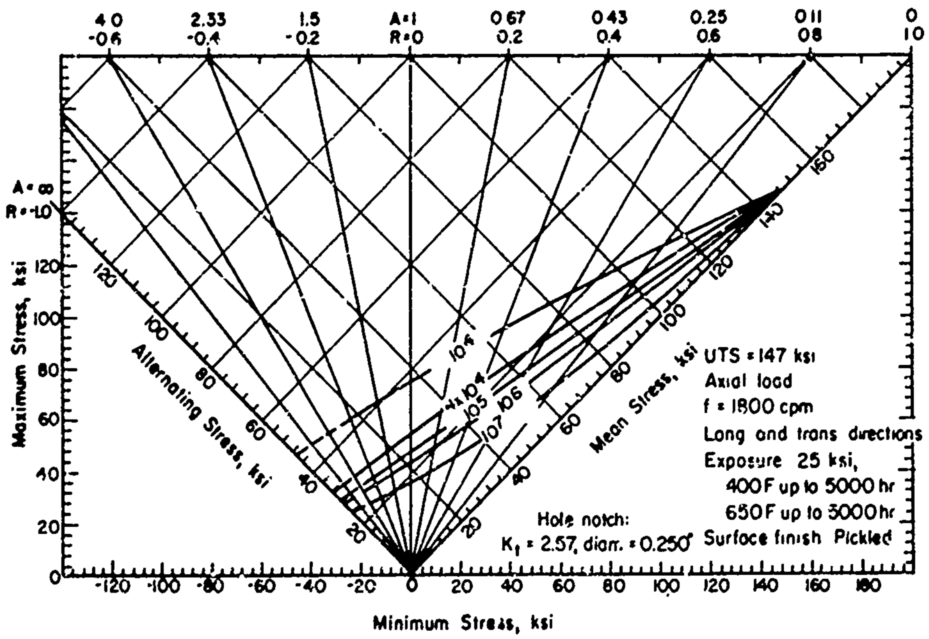

FIGURE 5-3.3.5-2. CONSTANT-LIFE FATIGUE DIAGRAM FOR DUPLEX-ANNEALED, NOTCHED, Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM TEMPERATURE IN EXPOSED AND UNEXPOSED CONDITIONS[43]

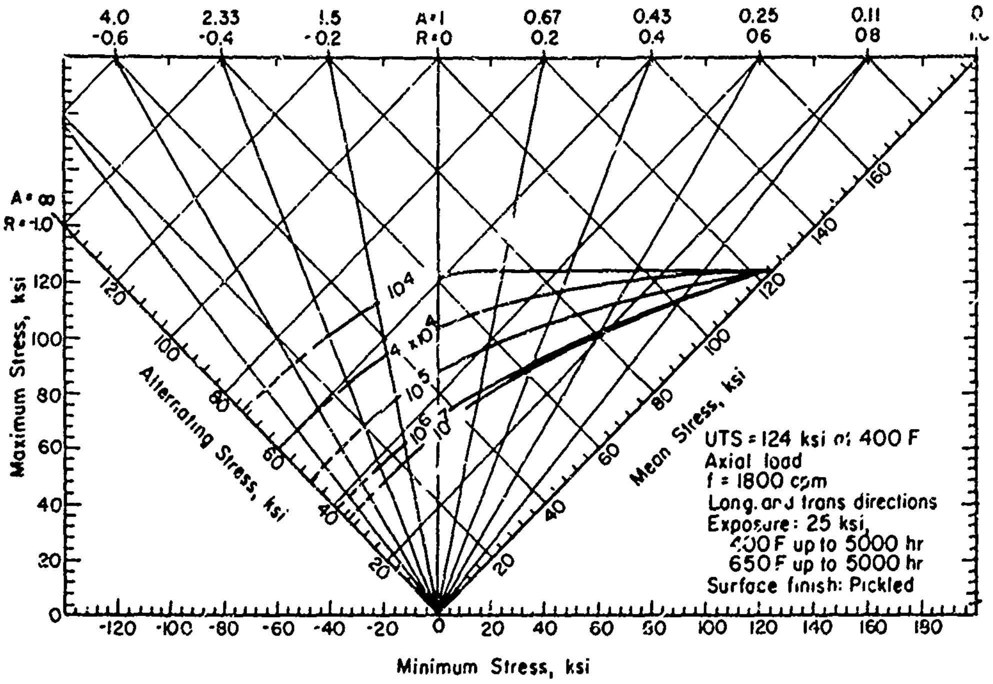

FIGURE 5-3.3.5-3. CONSTANT-LIFE FATIGUE DIAGRAM FOR DUPLEX-ANNEALED, UNNOTCHED, Ti-8Al-1Mo-1V ALLOY SHEET AT 400 F IN EXPOSED AND UNEXPOSED CONDITIONS(43)

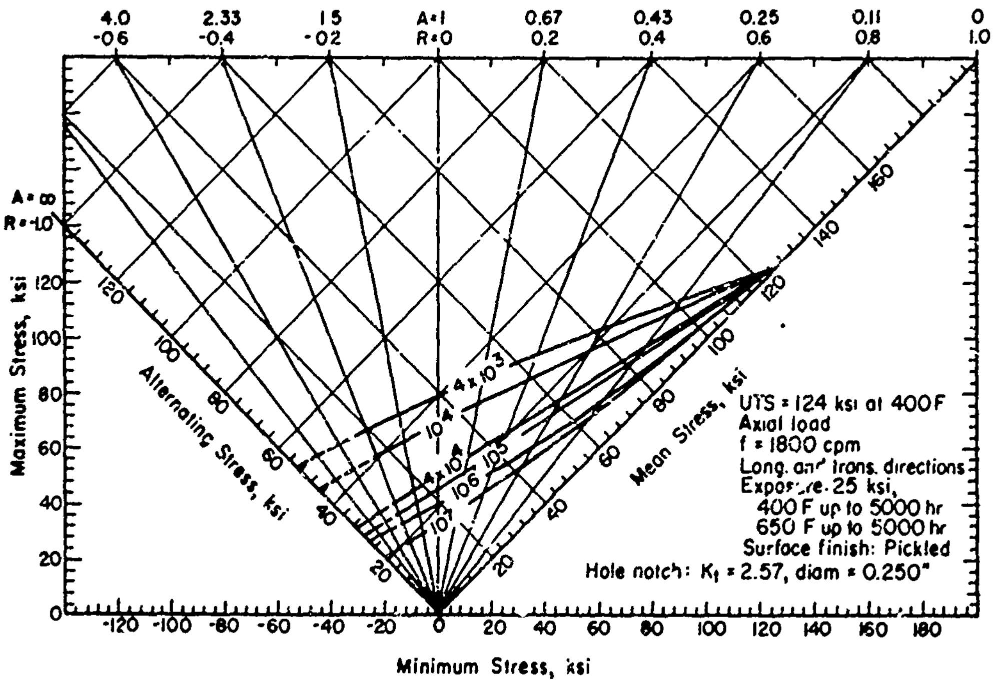

FIGURE 5-3.3.5-4. CONSTANT-LIFE FATIGUE DIAGRAM FOR DUPLEX-ANNEALED, NOTCHED Ti-8Al-1Mo-1V ALLOY SHEET AT 400 F IN EXPOSED AND UNEXPOSED CONDITIONS(43)

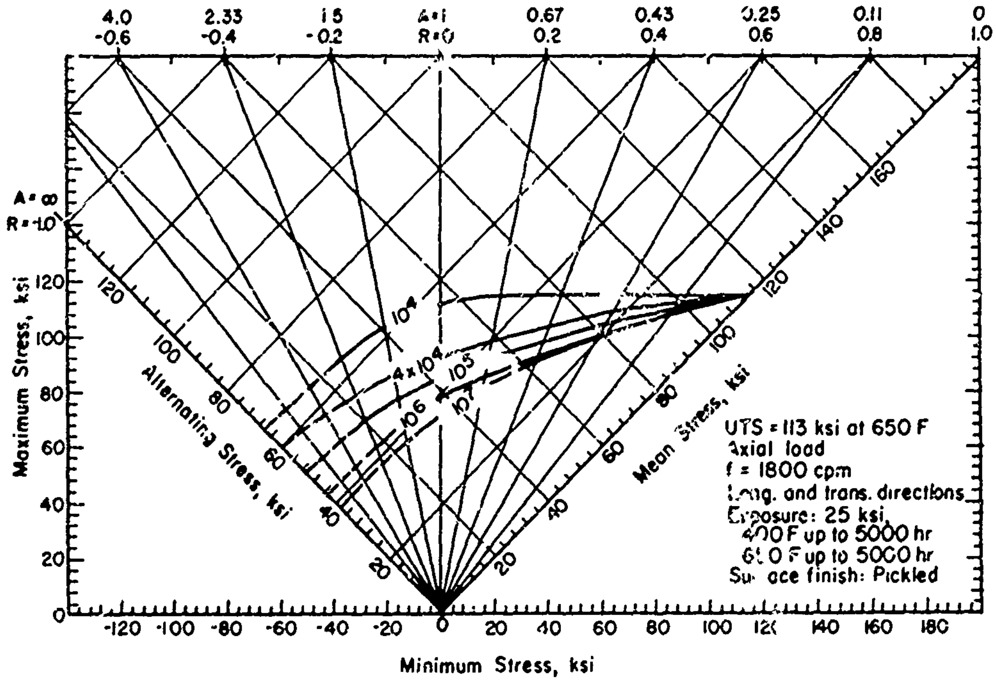

FIGURE 5-3.3.5-5. CONSTANT-LIFE FATIGUE DIAGRAM FOR DUPLEX-ANNEALED, UNNOTCHED, Ti-8Al-1Mo-1V ALLOY SHEET AT 650 F IN EXPOSED AND UNEXPOSED CONDITIONS(43)

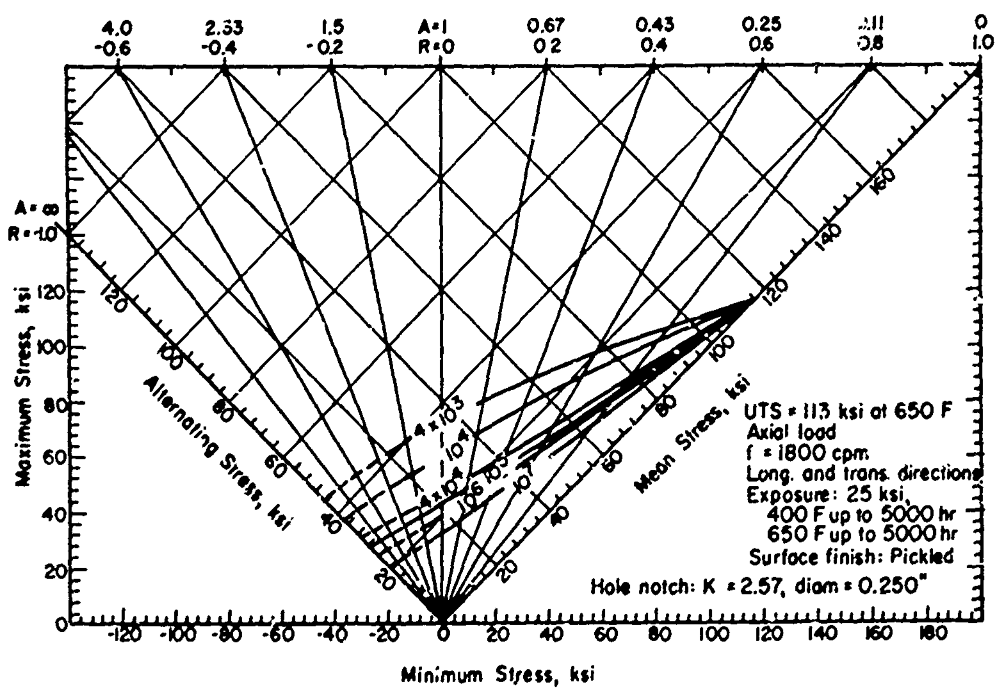

FIGURE 5-3.3.5-6. CONSTANT-LIFE FATIGUE DIAGRAM FOR DUPLEX-ANNEALED, NOTCHED, Ti-8Al-1Mo-1V ALLOY SHEET AT 650 F IN EXPOSED AND UNEXPOSED CONDITIONS(43)

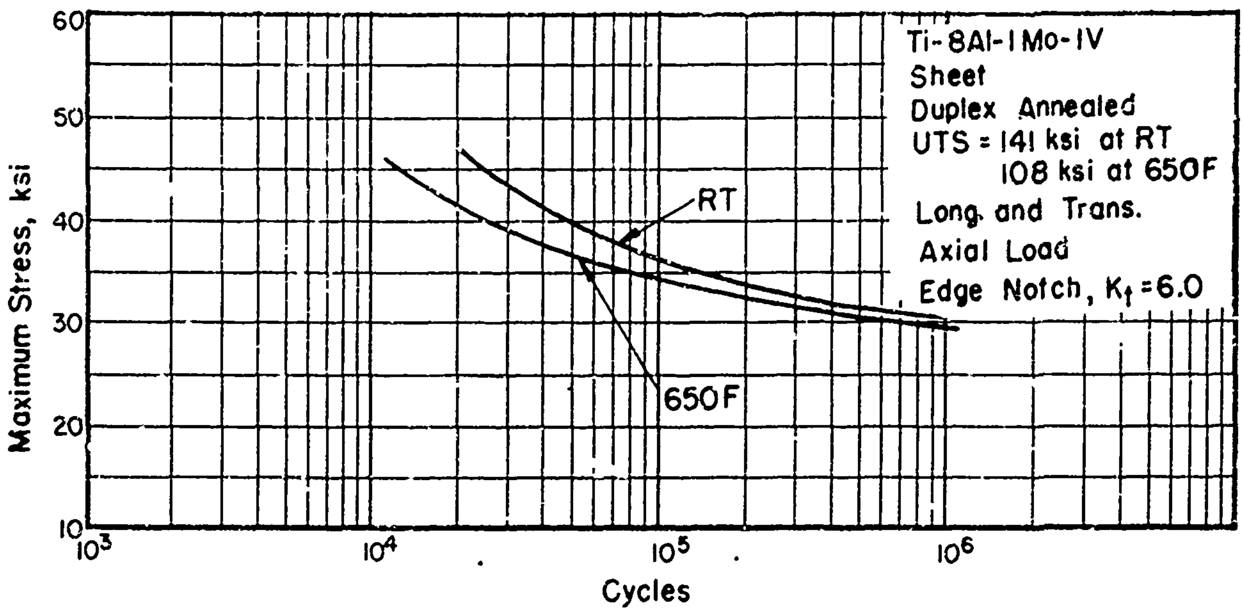

FIGURE 5-3.3.5-7. S-N DIAGRAM FOR EDGE-NOTCHED (K_t = 6.0, r = 0.010) SPECIMENS OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY WITH A MEAN STRESS OF 25 KSI[28]

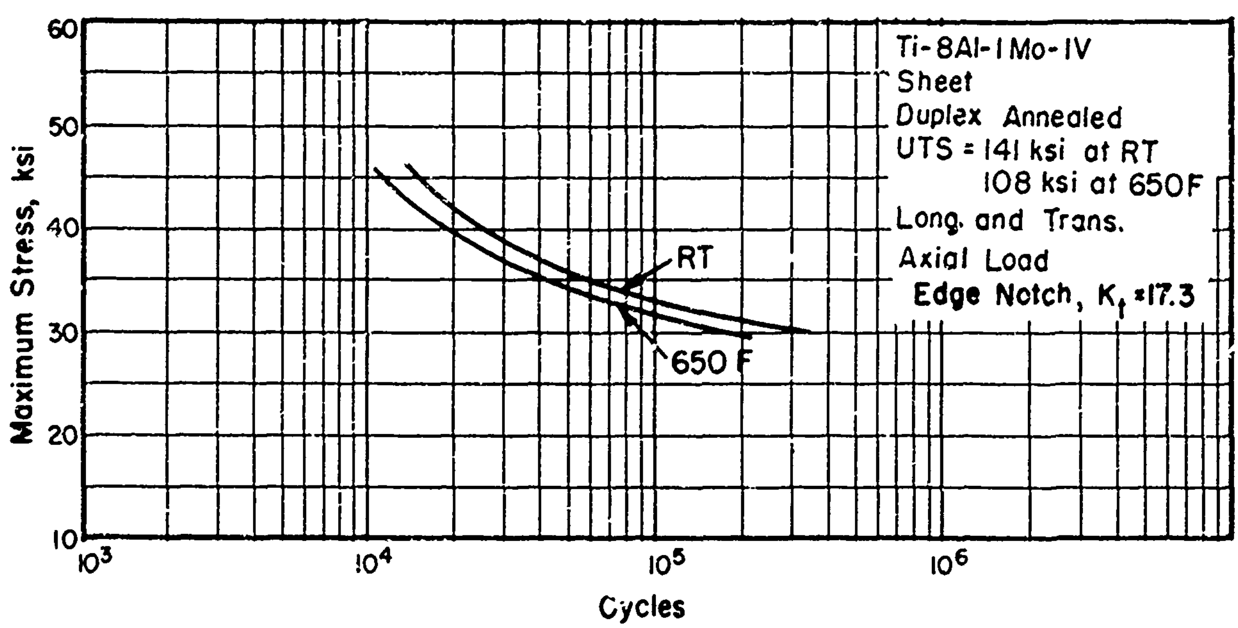

FIGURE 5-3.3.5-8. S-N DIAGRAM FOR EDGE-NOTCHED (K_t = 17.3, r = 0.001) SPECIMENS OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V ALLOY WITH A MEAN STRESS OF 25 KSI[28]

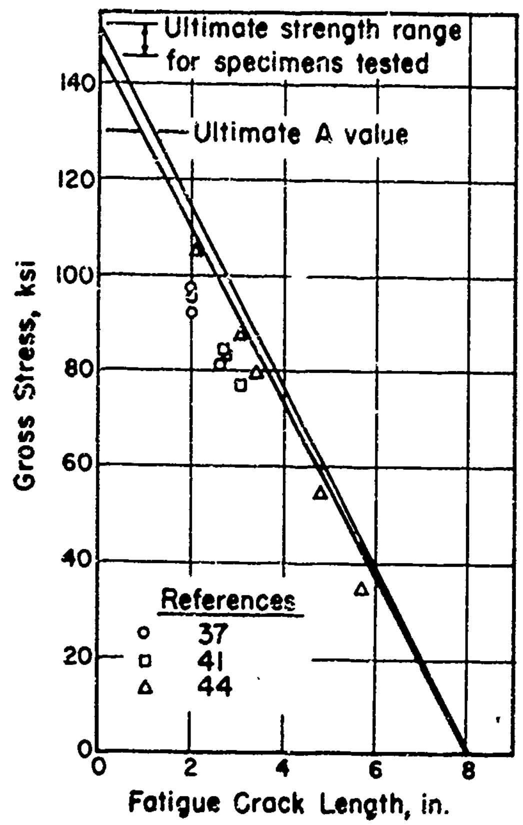

FIGURE 5-3.3.6-1. RESIDUAL STRENGTH DATA FOR 8-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY SHEET OF 0.050-INCH NOMINAL THICKNESS(37, 41, 44)

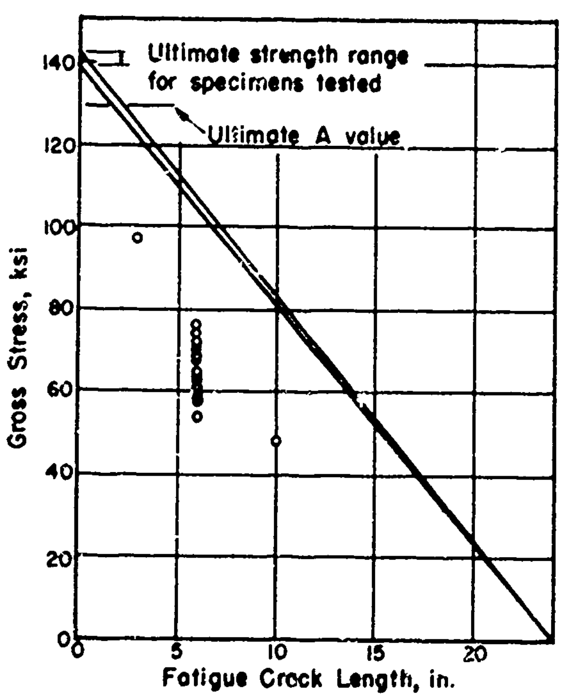

FIGURE 5-3.3.6-2. RESIDUAL STRENGTH DATA FOR 24-INCH-WIDE, DUPLEX-ANNEALED, Ti-8Al-1Mo-1V ALLOY SHEET OF 0.050-INCH NOMINAL THICKNESS(37)

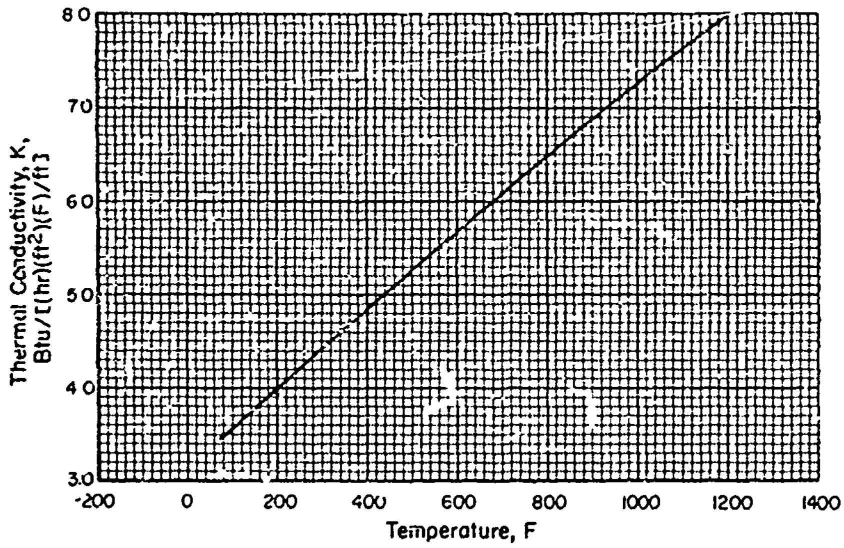

FIGURE 5-3.4-2. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY (K) OF Ti-8Al-1Mo-1V(29)

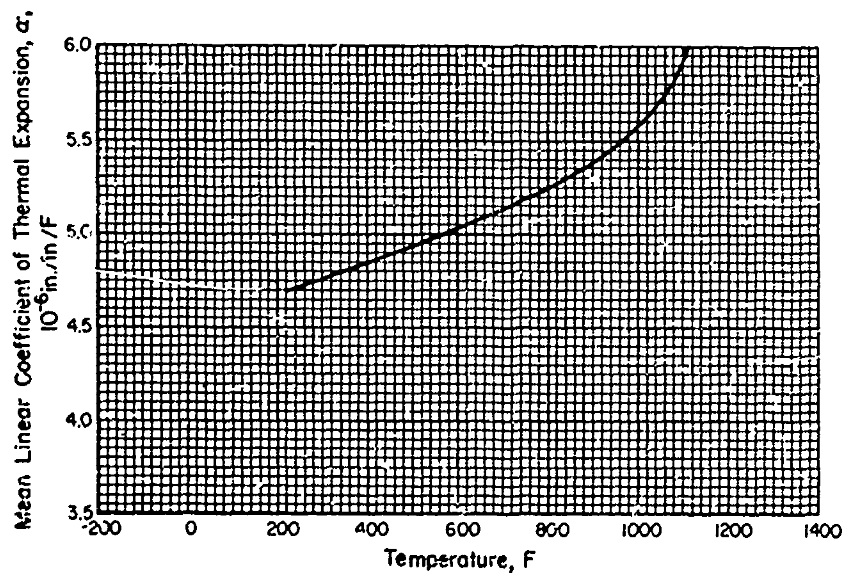

FIGURE 5-3.4-3. MEAN LINEAR COEFFICIENT OF THERMAL EXPANSION (α) OF Ti-8Al-1Mo-1V BETWEEN ROOM TEMPERATURE AND INDICATED TEMPERATURE(29)

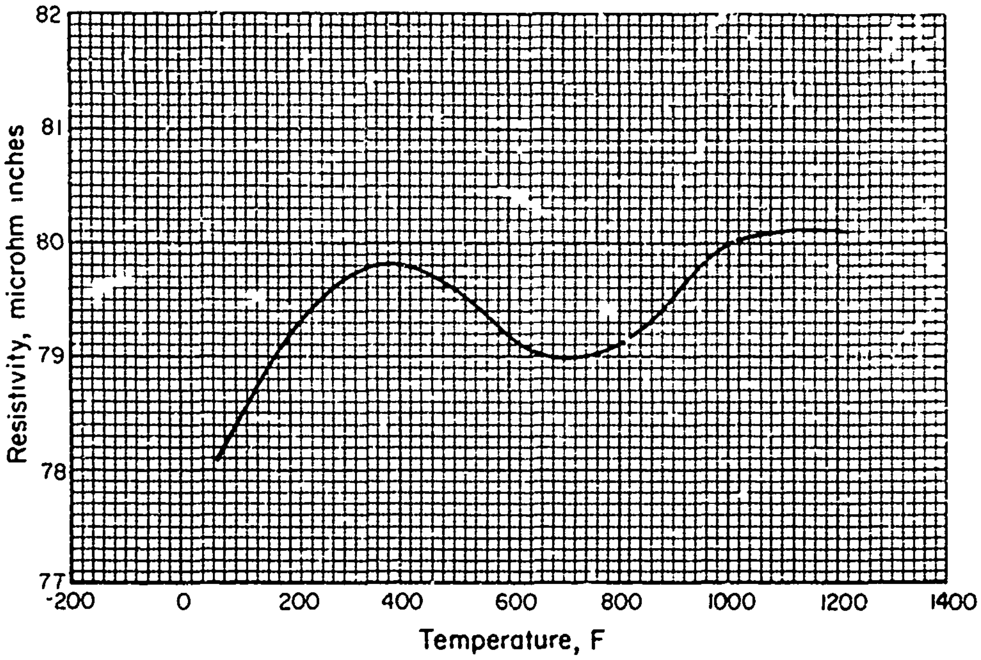

FIGURE 5-3.4-4. EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY (ρ) OF Ti-8Al-1Mo-1V[29]

5-4 Titanium Alloy Ti-6Al-4V

5-4.0 SPECIFICATIONS AND FORMS

This section covers titanium alloy Ti-6Al-4V of the following specifications and forms:

Specification	Form
MIL-T-9046	Sheet, strip, and plate
MIL-T-9047	Bars and forgings
AMS 4928, 4967	Bars and forgings
AMS 4935	Extrusions
MIL-H-81200	Heat treatment, all forms

At the present time, a variety of modified and developmental heat treatments are being investigated in order to obtain improved fracture resistance in this alloy. The following heat treatments are of special interest:

Designation	Description of Heat Treatment
Anneal (S,P)	1300 to 1350 F/1 hr/FC ($\leq$ 50 F/hr) to 800 F (MIL-H-81200)
Anneal (B,F,E)	1275 to 1325 F/2 hr/FC to 1000 F (AMS 4928)
Solution-treated and aged (1000 F) (all)	1725 to 1775 F/5 min. to 1 hr/WQ or AC + 985 to 1015 F/4 to 8 hr/AC (MIL-H-81200)
Solution-treated and aged (1250 F) (all)	1725 F/10 min./WQ + 1250 F/4 hr/AC
Beta processed (P,B,F,E)	Hot-worked above the beta transus (alternate: heat at 1850 to 1900 F/30 min./AC) Note: beta processing is followed by one of above-listed heat treatments.

Several of the above heat treatments, as well as modifications of these, have been used with bars and extrusions.

5-4.1 ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES

Table 5-4.1-1 summarizes the design mechanical properties of annealed titanium alloy Ti-6Al-4V at room temperature. Properties for solution-treated and aged ("heat-treated") products are summarized in Table 5-4.1-2. Properties for beta-processed material in each of several heat-treated conditions are tabulated separately in Table 5-4.1-3.

5-4.2 ENVIRONMENTAL EFFECTS FOR ANNEALED MATERIAL

5-4.2.1 Elevated-Temperature Effects

Data on the effects of temperature are presented in Figures 5-4.2.1-1 through 5-4.2.1-8.

5-4.2.3 Stress-Strain Curves

Typical tensile stress-strain curves for cryogenic, room, and elevated temperature are presented in Figure 5-4.2.3-1. A typical full-range stress-strain curve at room temperature is presented in Figure 5-4.2.3-2.

5-4.2.5 Fatigue Effects

A constant-life diagram for fatigue behavior is presented in Figure 5-4.2.5-1. A typical S-N diagram for notched specimens is presented in Figure 5-4.2.5-2. A typical S-N diagram for beta-processed and annealed extrusions at room temperature is presented in Figure 5-4.2.5-3.

5-4.2.6 Residual Strength Data

Residual-strength data are presented in Figures 5-4.2.6-1 and 5-4.2.6-2.

5-4.3 ENVIRONMENTAL EFFECTS FOR SOLUTION-TREATED AND AGED MATERIAL

5-4.3.1 Elevated-Temperature Effects

The effect of temperature data are presented in Figures 5-4.3.1-1 through 5-4.3.1-8.

5-4.3.3 Stress-Strain and Tangent Modulus Curves

Typical tensile and compressive stress-strain curves for room and elevated temperatures are presented in Figures 5-4.3.3-1 through 5-4.3.3-3. Typical compressive tangent modulus curves are presented in Figures 5-4.3.3-4 and 5-4.3.3-5. A typical full-range stress-strain curve at room temperature is presented in Figure 5-4.3.3-6.

5-4.3.4 Creep Effects

Creep data are presented in Figure 5-4.3.4-1.

5-4.3.5 Fatigue Effects

Constant-life diagrams for fatigue behavior at room and elevated temperatures are presented in Figures 5-4.3.5-1 through 5-4.3.5-3. A typical S-N diagram for unnotched forgings is presented in Figure 5-4.3.5-4. A typical S-N diagram for notched specimens is presented in Figure 5-4.3.5-5. A typical S-N diagram for beta-processed + solution-treated and aged (1000 F) extrusions at room temperature is presented in Figure 5-4.3.5-6. A typical S-N diagram for beta-processed + solution-treated and aged (1250 F) extrusions at room temperature is presented in Figure 5-4.3.5-7.

5-4.4 THERMOPHYSICAL EFFECTS

The effect of temperature on physical properties is displayed in Figures 5-4.4-1 through 5-4.4-4.

TABLE 5-4.1-1. ROOM TEMPERATURE DESIGN MECHANICAL PROPERTIES OF ANNEALED Ti-6Al-4V

Alloy	MIL-T-9046 Type III Composition C						MIL-T-9047 Type III Composition A
Form	Sheet				Plate		Bar, Forgings & Extrusions
Condition	Annealed						
Thickness or diameter, in.	<0.025	0.025-0.187		0.025-0.187	≥0.188		<3
Basis	S^b	A	B	$S^{b,c}$	A	B	S
Mechanical properties:							
F_{tu}, ksi	130	133	138	130	130	135	130
F_{ty}, ksi	120	126	127	120	120	125	120
F_{cy}, ksi	126	130	133	126	126	131	126
F_{su}, ksi	76	78	80	76	76	79	80
F_{bru}, ksi:							
(e/D = 1.5)	191	195	200	191	191	198	196
(e/D = 2.0)	244	249	255	244	244	255	248
F_{bry}, ksi:							
(e/D = 1.5)	163	168	172	163	163	170	174
(e/D = 2.0)	198	204	210	198	198	206	205
e, per cent:							
In 2 in.	-	(a)	-	(a)	10	-	-
In 4 D	-	-	-	-	-	-	10
E, 10^6 psi	16.0						
E_c, 10^6 psi	16.4						
G, 10^6 psi	6.1						
μ	0.32						
n	-						
ω, lb/in.^{3}	0.160						

(a) 8-0.025 to 0.062 inch, inclusive 10-0.063 to 0.187 inch, inclusive.

(b) Represents AMS 4911 requirements for F_{tu} and F_{ty}; note that these are lower than MIL-T-9046.

(c) Values in this column apply to material reannealed after aging.

TABLE [illegible] [illegible] MECHANICAL PROPERTIES OF SOLUTION-TREATED AND [illegible]

Alloy	MIL-T-9046 Type III Composition C					
Form	Sheet, strip, and plate					
Condition	Solution treated and Aged at 1000 F					
Thickness or diameter, in.	≤0.187		0.188 to 0.750	0.751 to 1.000	1.001 to 2.000	2.001 to 4.000
Basis	A	B	S	S	S	S
Mechanical properties:						
F_{tu}, ksi	157	162	160	150	145	130
F_{ty}, ksi	143	148	145	140	135	120
F_{cy}, ksi						
L	152	157	[illegible]	[illegible]	[illegible]	[illegible]
T	160	165	[illegible]	[illegible]	[illegible]	[illegible]
F_{su}, ksi	98	101	[illegible]	[illegible]	(90)	[illegible]
F_{bru}, ksi:						
(e/D = 1.5)	232	239	[illegible]	[illegible]	[illegible]	(192)
(e/D = 2.0)	281	290	[illegible]	[illegible]	[illegible]	[illegible]
F_{bry}, ksi:						
(e/D = 1.5)	207	214	[illegible]	[illegible]	[illegible]	(174)
(e/D = 2.0)	229	237	[illegible]	[illegible]	[illegible]	(192)
e, per cent:	(a)					
In 2 in.			6	6	6	6
In 4 D	-	-	-	-	-	-
E, 10^6 psi	16.0					
E_c, 10^6 psi	16.4					
G, 10^6 psi	6.1					
μ	0.32					
n	-					
ω, lb/in.^{3}	0.160					

Values in parentheses () are tentative values.

(a) 3 - 0.025 to 0.032 inch; 4 - 0.033 to 0.049 inch; 5 - 0.050 inch and over.

Alloy	MIL-T-9047D Type III Composition A												
Form	Bars and Forgings												
Condition	Solution-treated and aged per MIL-H-81200												
Thickness or diameter, in.	≤.5		>.5,≤1			>1,≤1.5			>1.5,<2			>2,≤3	>3,≤4
Width, in.	≤.5	>.5,≤8	≤1	>1,≤4	>4,≤8	≤1.5	>1.5,≤4	>4,≤8	≤2	>2,≤4	>4,≤8	≤8	≤8
Basis	S	S	S	S	S	S	S	S	S	S	S	S	S
Mechanical properties:													
F_{tu}, ksi	[illegible]	[illegible]	160	155	150	155	150	145	150	145	140	135	130
F_{ty}, ksi	[illegible]	[illegible]	150	145	140	145	140	135	140	135	130	125	120
F_{cy}, ksi	[illegible]	(157)	(157)	[illegible]	(147)	(152)	(147)	(141)	(147)	(141)	(136)	(131)	(126)
F_{su}, ksi	[illegible]	[illegible]	[illegible]	(95)	[illegible]	(95)	(92)	(89)	(92)	(89)	(86)	(83)	(80)
F_{bru}, ksi:													
(e/D = 1.5)	[illegible]	[illegible]	(241)	(233)	(226)	(233)	(226)	(218)	(226)	(218)	(211)	(203)	(196)
(e/D = 2.0)	[illegible]	[illegible]	(305)	(295)	(286)	(295)	(286)	(276)	(286)	(276)	(267)	(257)	(248)
F_{bry}, ksi:													
(e/D = 1.5)	[illegible]	[illegible]	(227)	(210)	(203)	(210)	(203)	(195)	(203)	(195)	(188)	(181)	(174)
(e/D = 2.0)	[illegible]	[illegible]	(256)	(248)	(239)	(248)	(239)	(230)	(239)	(230)	(222)	(213)	(205)
e, per cent:													
L	10	10	10	10	10	10	10	10	10	10	10	10	8
T	—	10	—	10	10	—	10	10	—	10	10	8	6
E, 10^6 psi	16.0												
E_c, 10^6 psi	16.4												
G, 10^6 psi	6.1												
μ	0.32												
n	--												
ω, lb/in.^{3}	0.160												

Values in parentheses () are tentative values

TABLE 5-4.1-2 (Continued)

Alloy	AMS 4935				
Form	Extrusions[a]				
Condition	Solution Treated and Age at 1000° F				
Thickness or diameter, in.	≤ 0.625[b]		≤ 1	$>1, \leq 2$	$>2, \leq 3$
Basis	A	B	S[c]	S[c]	S[c]
Mechanical properties:					
F_{tu}, ksi	165	173	160	150	140
F_{ty}, ksi	146	151	150	140	130
F_{cy}, ksi	(153)	(158)	(157)	(147)	(136)
F_{su}, ksi	(101)	(106)	(98)	(92)	(86)
F_{bru}, ksi:					
(e/D = 1.5)	(248)	(260)	(241)	(226)	(211)
(e/D = 2.0)	(315)	(330)	(305)	(286)	(267)
F_{bry}, ksi:					
(e/D = 1.5)	(211)	(218)	(217)	(203)	(188)
(e/D = 2.0)	(249)	(258)	(254)	(239)	(222)
e, per cent:					
In 2 in.					
In 4 D	5	-	10	8	8
E, 10^6 psi	16.0				
E_c, 10^6 psi	16.4				
G, 10^6 psi	6.1				
μ	0.32				
n	-				
ω, lb/in.^{3}	0.160				

Values in parentheses () are tentative values.

a Properties applicable to longitudinal direction only.
b Diameter of inscribed circle.
c The specified values for F_{tu}, F_{ty}, and e shown in these columns appear to be optimistic and should be validated further before use in design.

TABLE 5-4.1-3. ROOM TEMPERATURE DESIGN MECHANICAL PROPERTIES OF BETA-PROCESSED Ti-6Al-4V

Alloy	MIL-T-9046 Type III Composition C				MIL-T-9047 Type III Composition A
Form	Plate				Bar and Forgings
Condition	Beta + Anneal		Beta + STA (1000F)	Beta + STA (1250F)	Beta + Anneal
Thickness or diameter, in.	0.188-0.250	0.251-0.500	0.188-0.500	0.188-0.750	--
Basis	S[a]	S[a]	S[b]	S[a,c]	S[a]
Mechanical properties:					
F_{tu}, ksi	125	120	(150)	130	125
F_{ty}, ksi	115	110	(135)	120	115
F_{cy}, ksi	(121)	(115)	(142)	(126)	(121)
F_{su}, ksi	(73)	(70)	(79)	(76)	(73)
F_{bru}, ksi:					
(e/D = 1.5)	(183)	(176)	(220)	(190)	(183)
(e/D = 2.0)	(234)	(225)	(280)	(243)	(234)
F_{bry}, ksi:					
(e/D = 1.5)	(156)	(149)	(183)	(163)	(156)
(e/D = 2.0)	(190)	(182)	(223)	(198)	(190)
e, per cent:					
In 2 in.	8	10	4	(4)	-
In 4 D	-	-	-		8
E, 10^6 psi	16.0				
E_c, 10^6 psi	16.4				
G, 10^6 psi	6.1				
μ	0.32				
n	-				
ω, lb/in.^{3}	0.160				

Values in parentheses () are tentative values.

a Producers guaranteed properties, supported by available data.
b Suggested minimum properties based on limited supporting data.
c Limited data indicate properties in the longitudinal direction may be lower than shown.
d 8 - 0.188 to 0.250 inch;
10 - 0.251 to 0.750 inch.

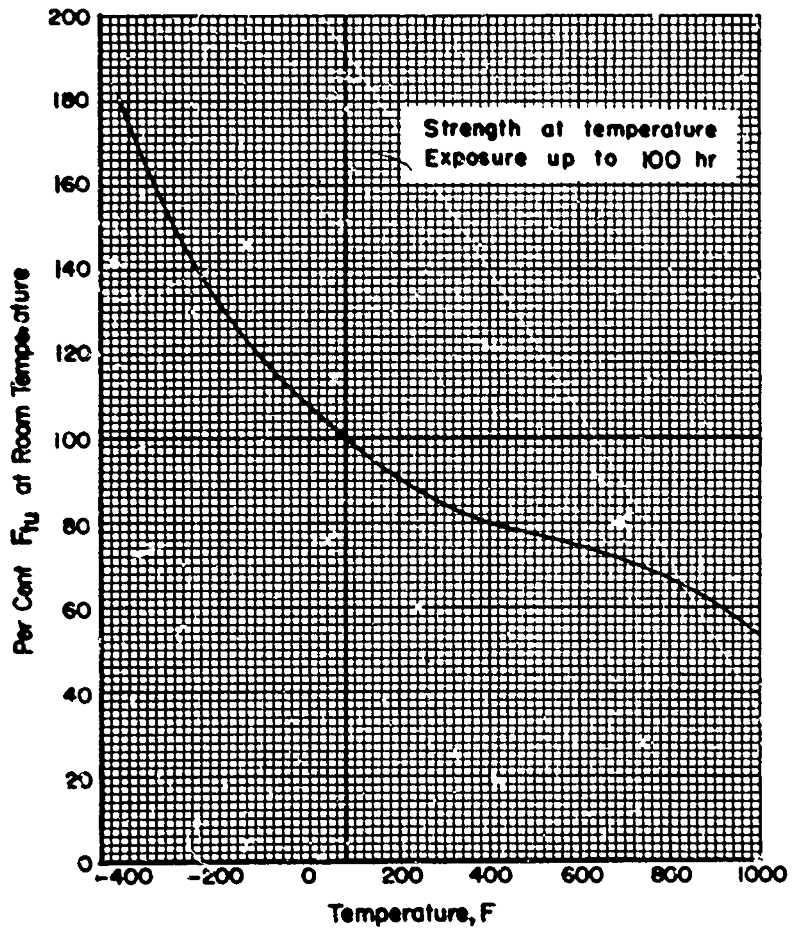

FIGURE 5-4.2.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF ANNEALED Ti-6Al-4V SHEET AND BAR

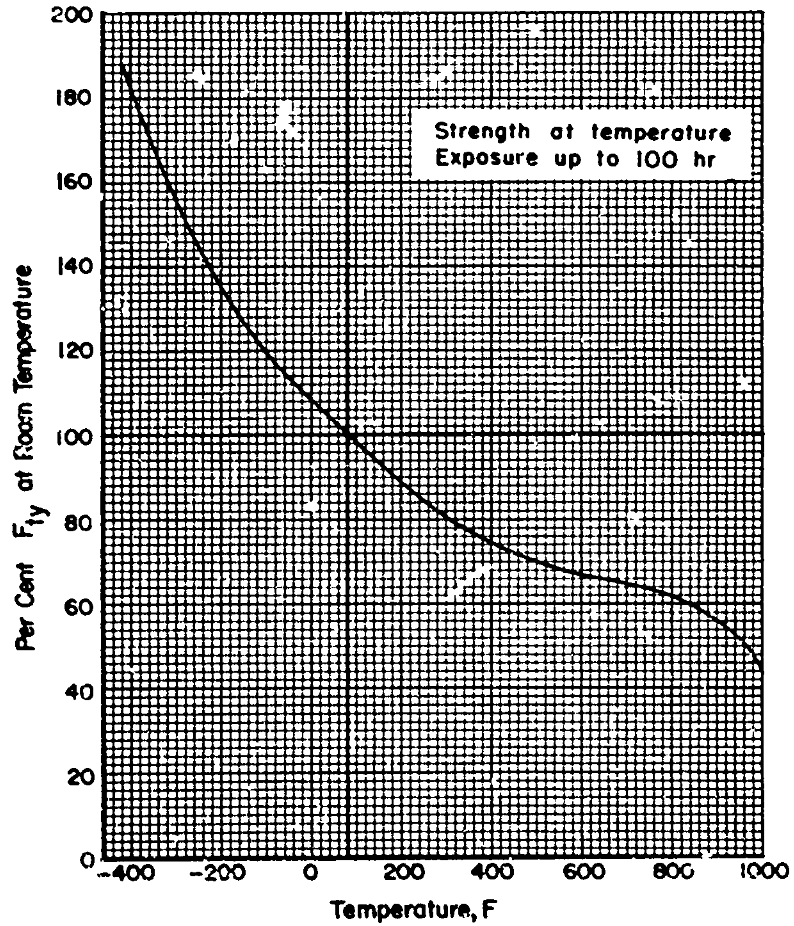

FIGURE 5-4.2.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF ANNEALED Ti-6Al-4V SHEET AND BAR

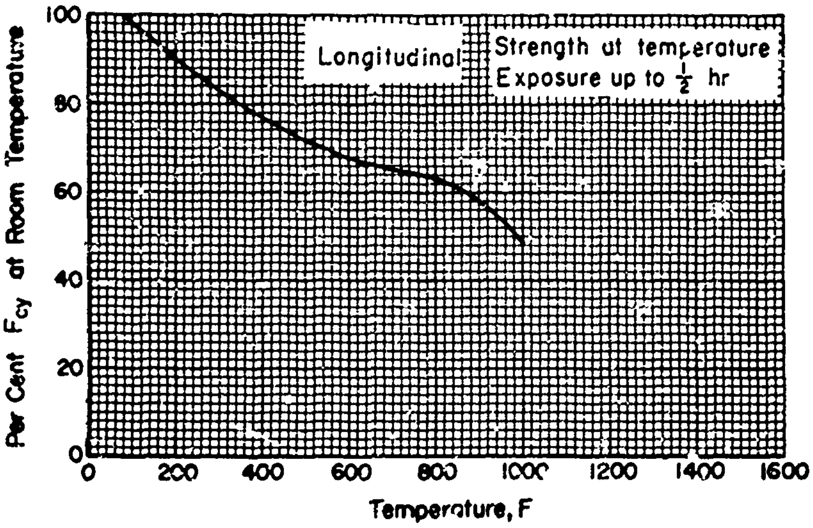

FIGURE 5-4.2.1-3. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF ANNEALED Ti-6Al-4V ALLOY SHEET AND BAR

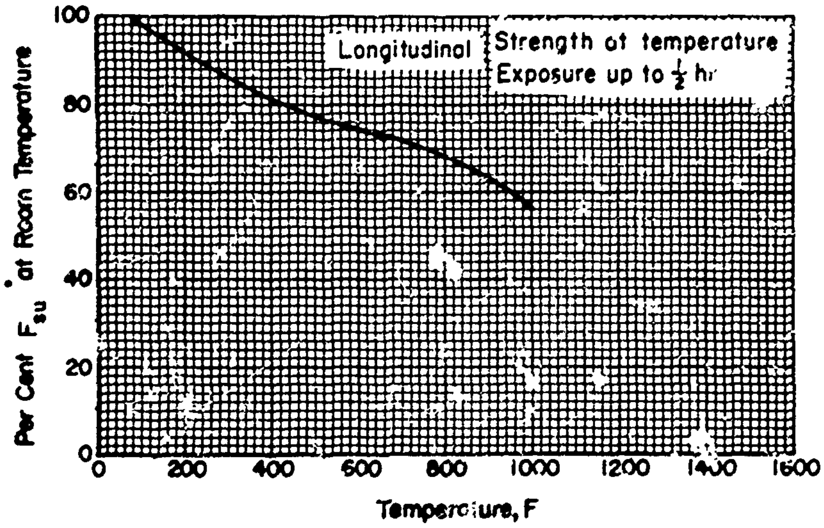

FIGURE 5-4.2.1-4. EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF ANNEALED Ti-6Al-4V ALLOY SHEET AND BAR

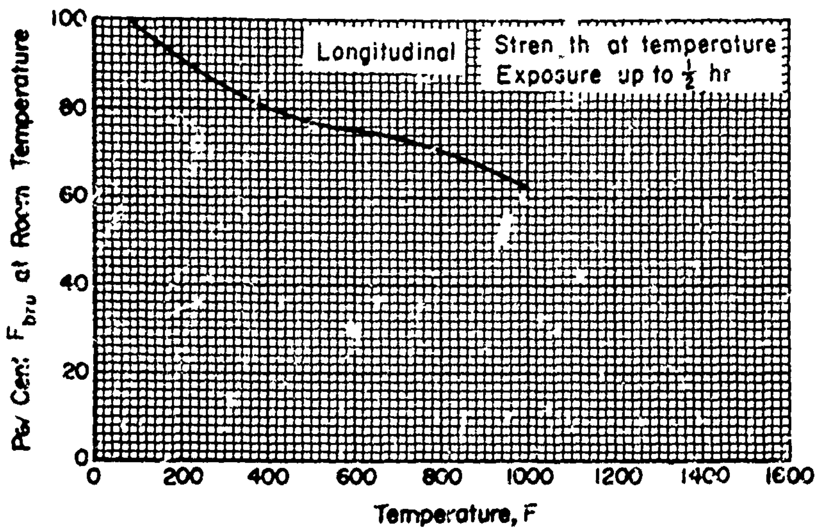

FIGURE 5-4.2.1-5. EFFECT OF TEMPERATURE ON THE ULTIMATE BEARING STRENGTH (F_{bru}) OF ANNEALED Ti-6Al-4V ALLOY SHEET AND BAR

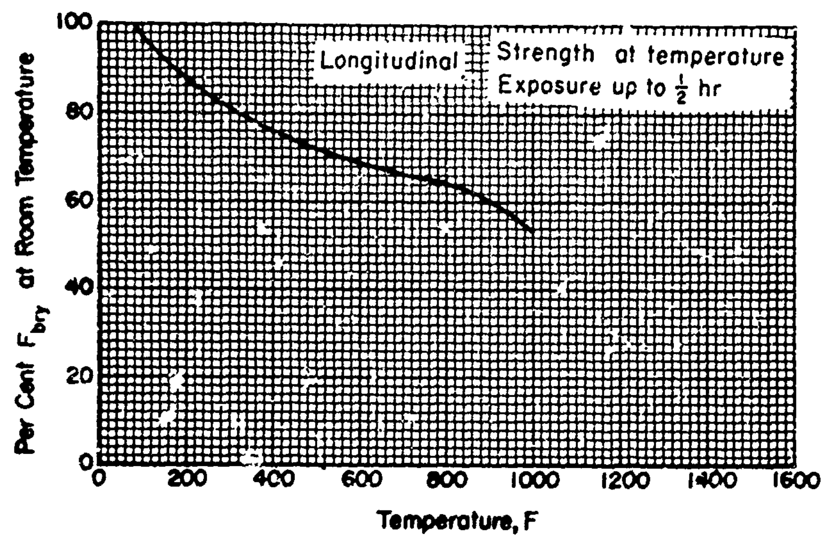

FIGURE 5-4.2.1-6. EFFECT OF TEMPERATURE ON THE BEARING YIELD STRENGTH (F_{bry}) OF ANNEALED Ti-6Al-4V ALLOY SHEET AND BAR

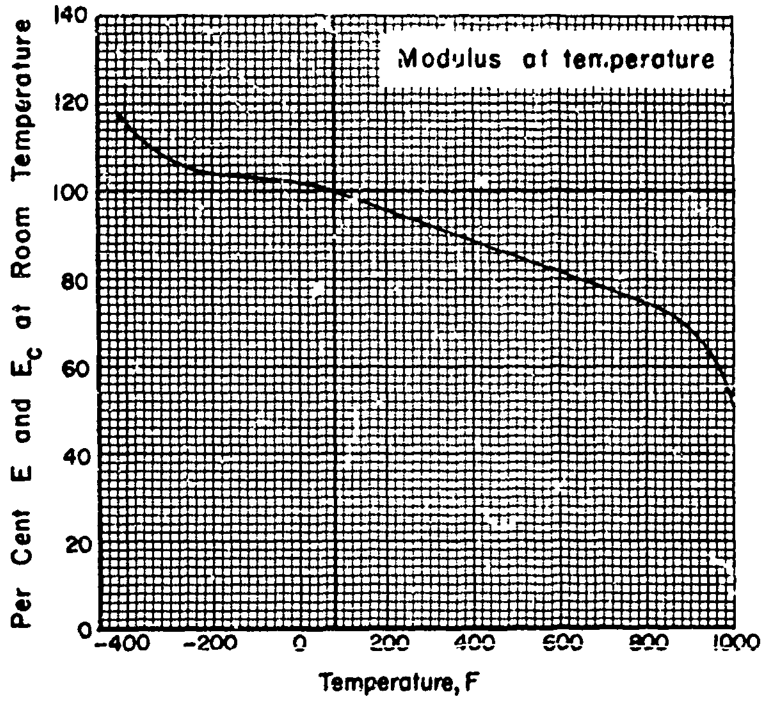

FIGURE 5-4.2.1-7. EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E AND E_c) OF ANNEALED Ti-6Al-4V SHEET AND BAR

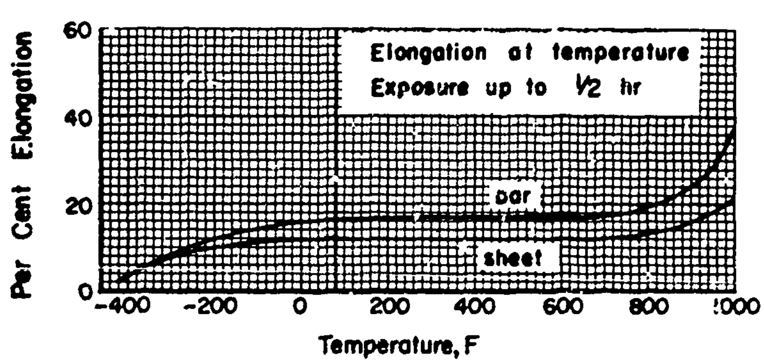

FIGURE 5-4.2.1-8. EFFECT OF TEMPERATURE ON THE ELONGATION OF ANNEALED Ti-6Al-4V SHEET AND BAR

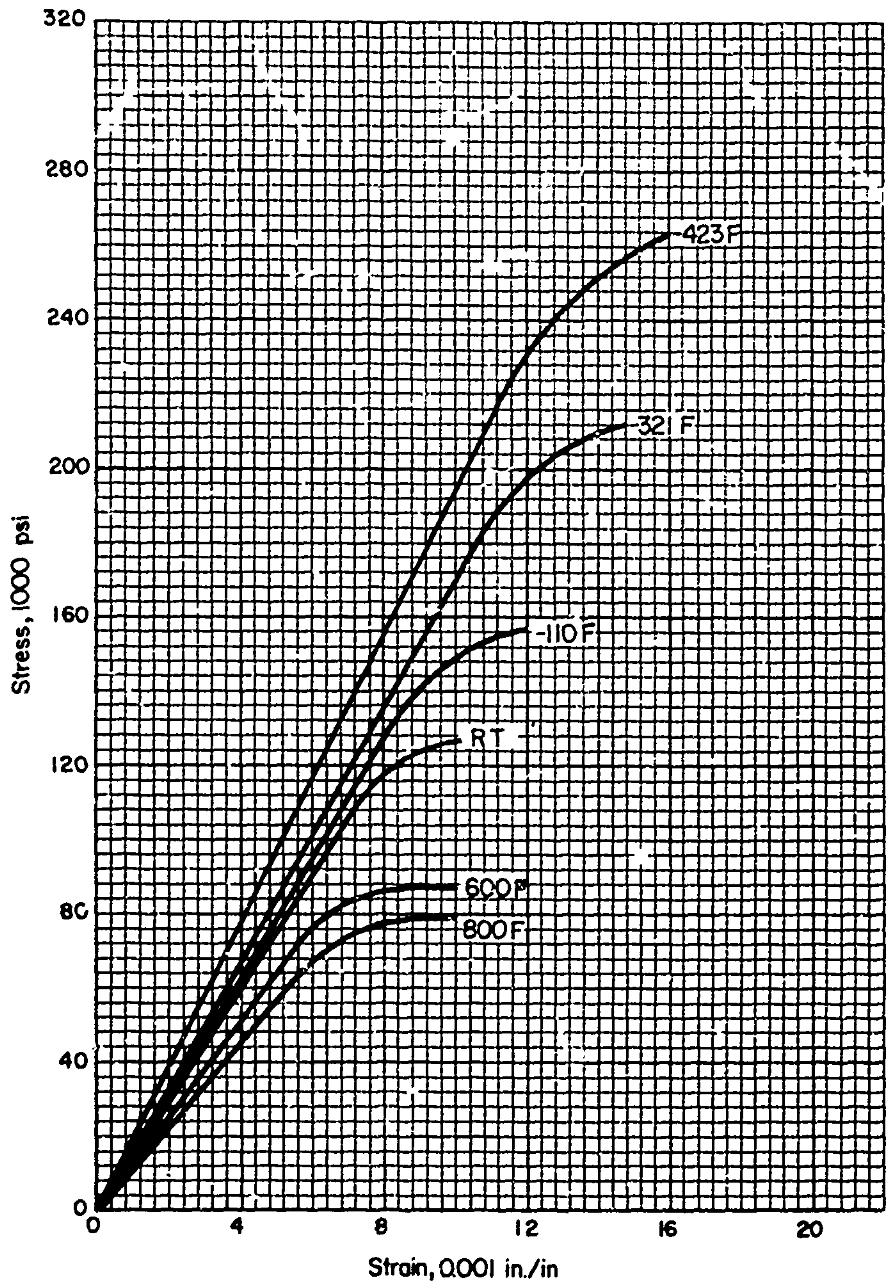

FIGURE 5-4.2.3-1. TYPICAL TENSILE STRESS-STRAIN CURVES AT CRYOGENIC, ROOM, AND ELEVATED TEMPERATURES FOR ANNEALED Ti-6Al-4V

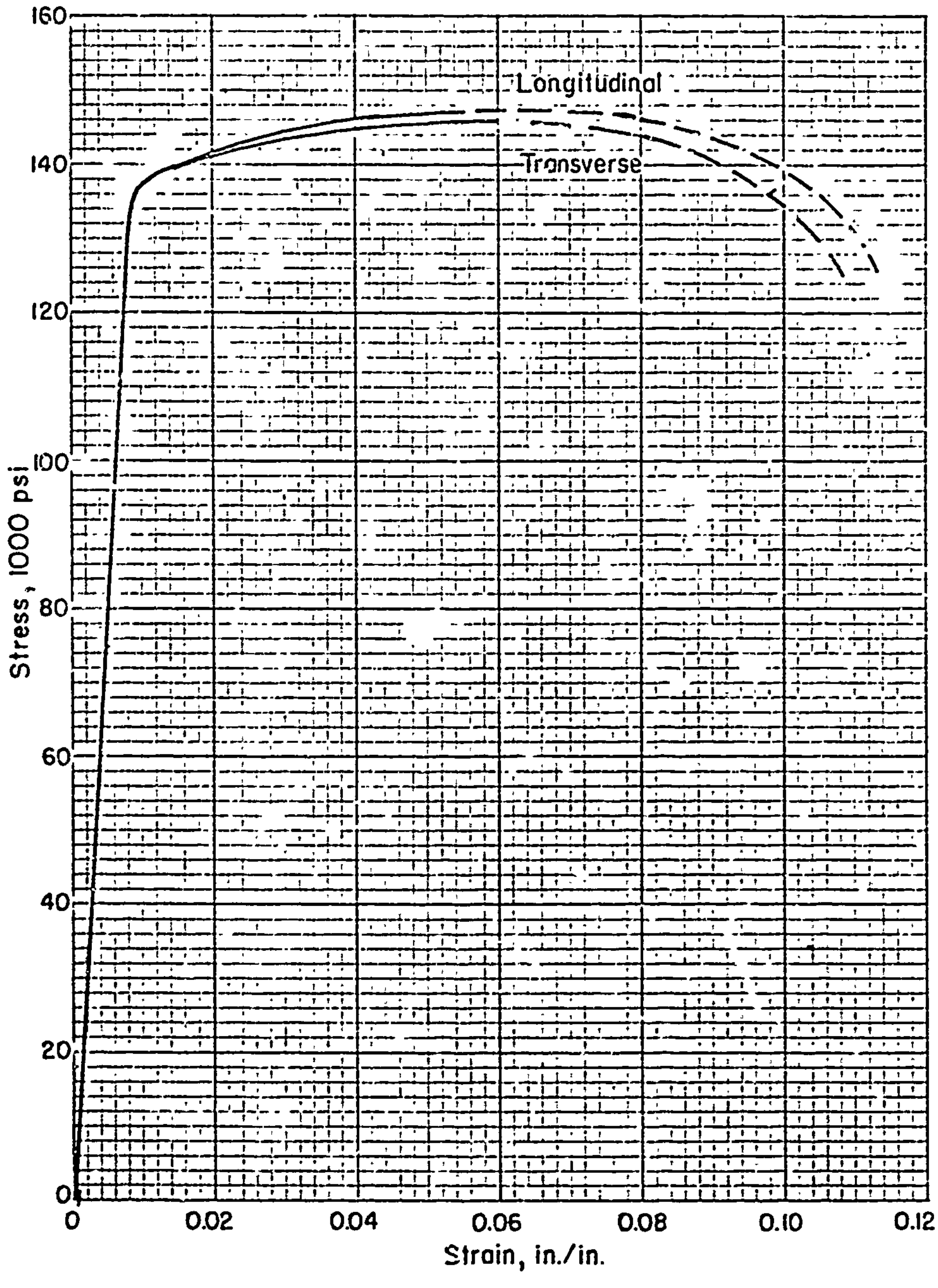

FIGURE 5-4.2.3-2. TYPICAL FULL-RANGE STRESS-STRAIN CURVES FOR ANNEALED Ti-6Al-4V SHEET AT ROOM TEMPERATURE[47]

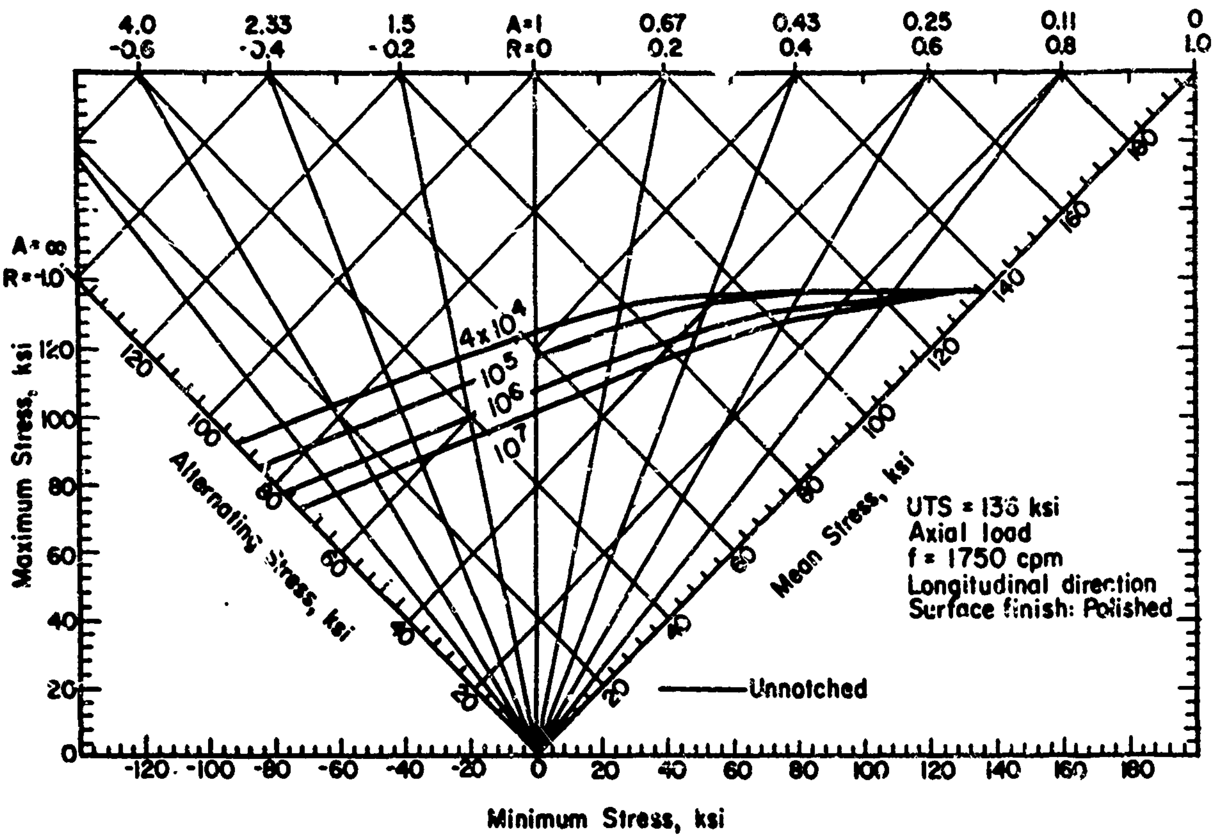

FIGURE 5-4.2.5-1. CONSTANT-LIFE FATIGUE DIAGRAM FOR MILL-ANNEALED Ti-6Al-4V ALLOY BAR AT ROOM TEMPERATURE(1)

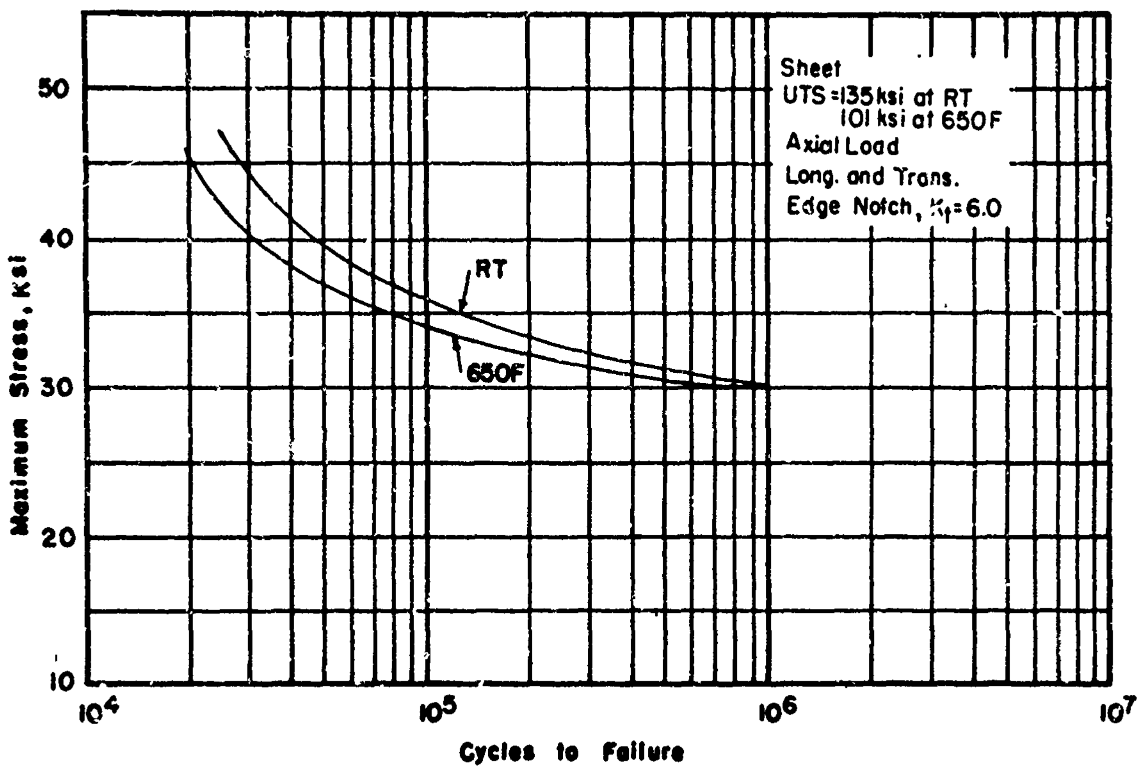

FIGURE 5-4.2.5-2. S-N DIAGRAM FOR EDGE-NOTCHED (K_t = 6, r = 0.010 in) SPECIMENS OF ANNEALED Ti-6Al-4V ALLOY SUBJECTED TO A MEAN STRESS OF 25 KSI[28]

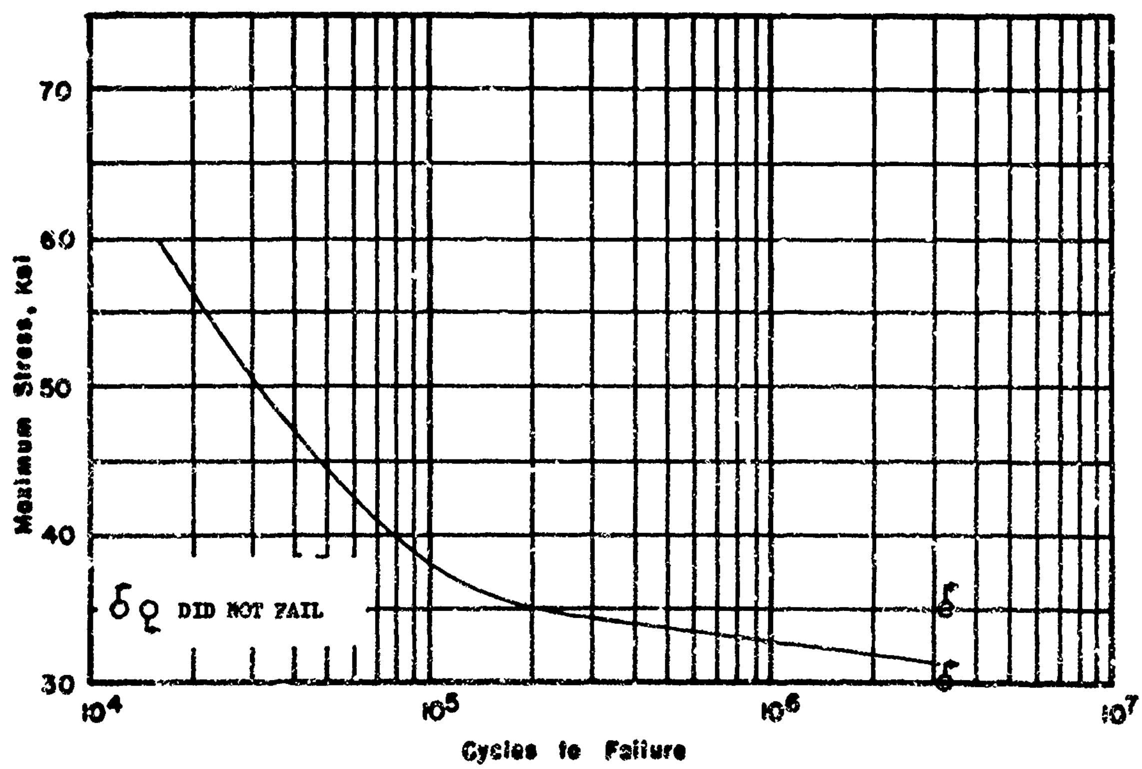

FIGURE 5-4.2.5-3. S-N DIAGRAM FOR NOTCHED (K_t = 2.58) SPECIMENS OF BETA-TREATED PLUS ANNEALED AT 1300 F FOR 2 HOURS AND AIR COOLED ANGLE EXTRUSION OF Ti-6Al-4V ALLOY[69]

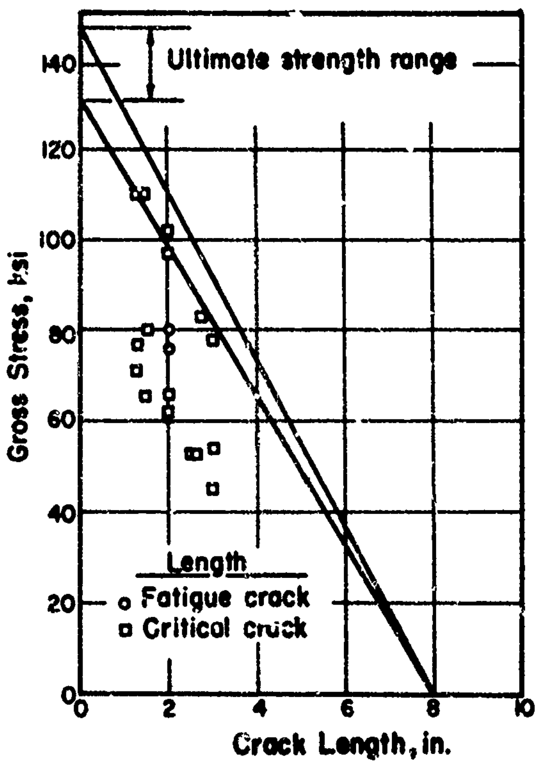

FIGURE 5-4.2.6-1. RESIDUAL STRENGTH DATA FOR 8-INCH-WIDE, MILL-ANNEALED Ti-6Al-4V ALLOY SHEET OF 0.025-INCH NOMINAL THICKNESS[3, 37]

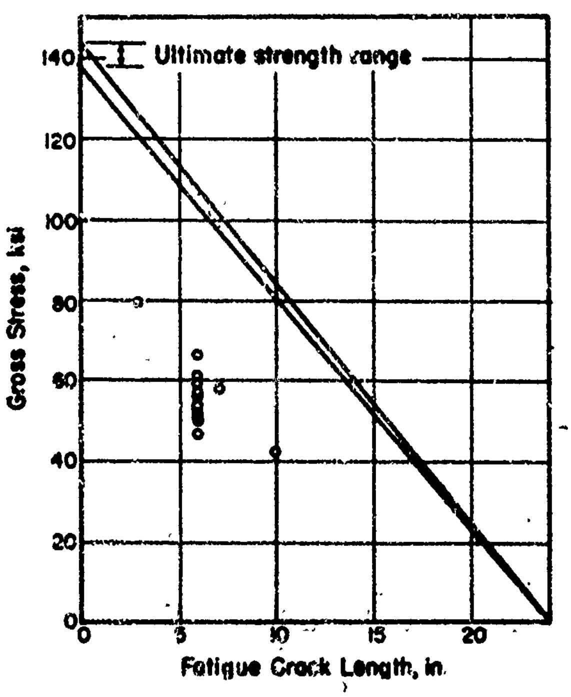

FIGURE 5-4.2.6-2. RESIDUAL STRENGTH DATA FOR 24-INCH-WIDE, MILL-ANNEALED, Ti-6Al-4V ALLOY SHEET OF 0.050-INCH NOMINAL THICKNESS[37]

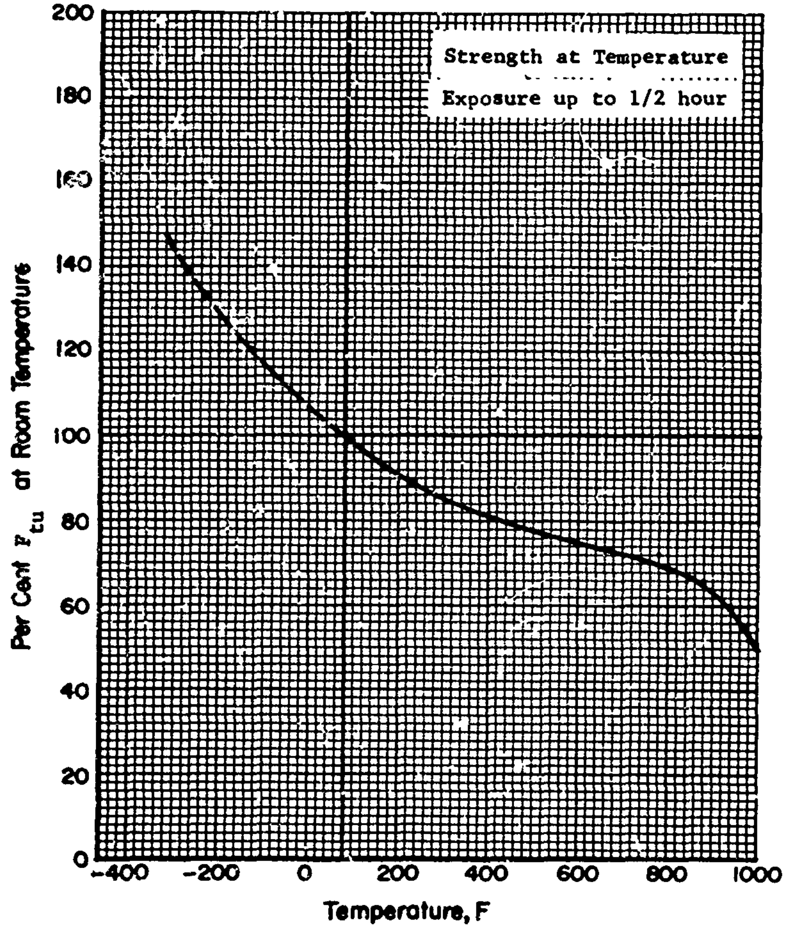

FIGURE 5-4.3.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY

Note: Tentative extension of this curve below 80 degrees F not included in MIL-HDBK-5

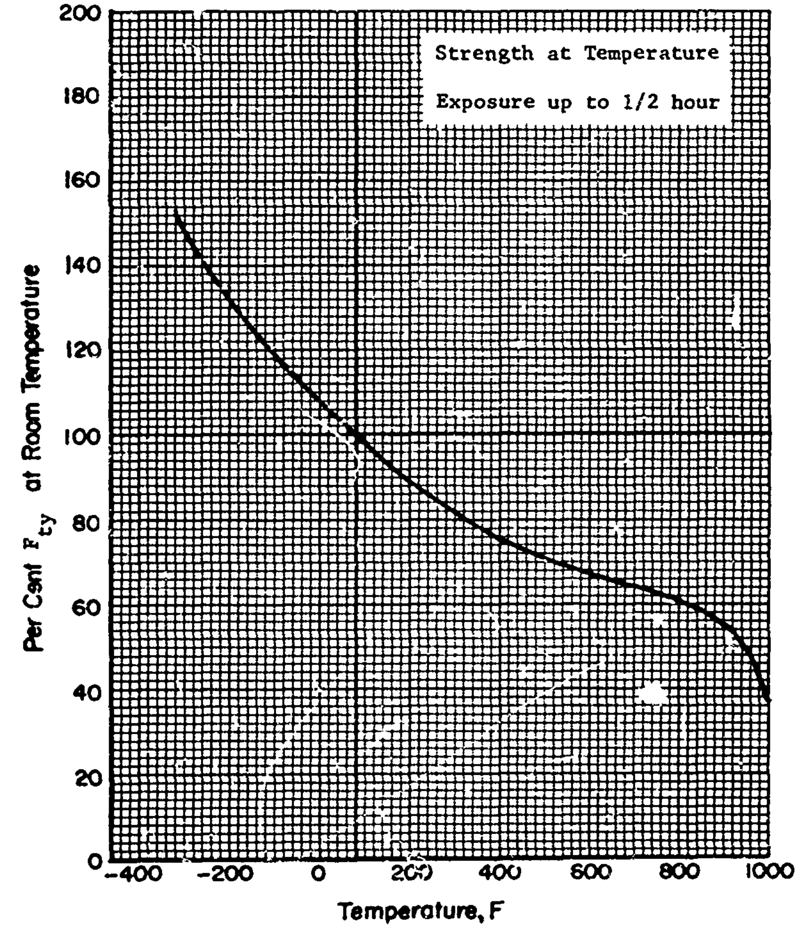

FIGURE 5-4.3.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY

Note: Tentative extension of this curve below 80 degrees F not included in MIL-HDBK-5

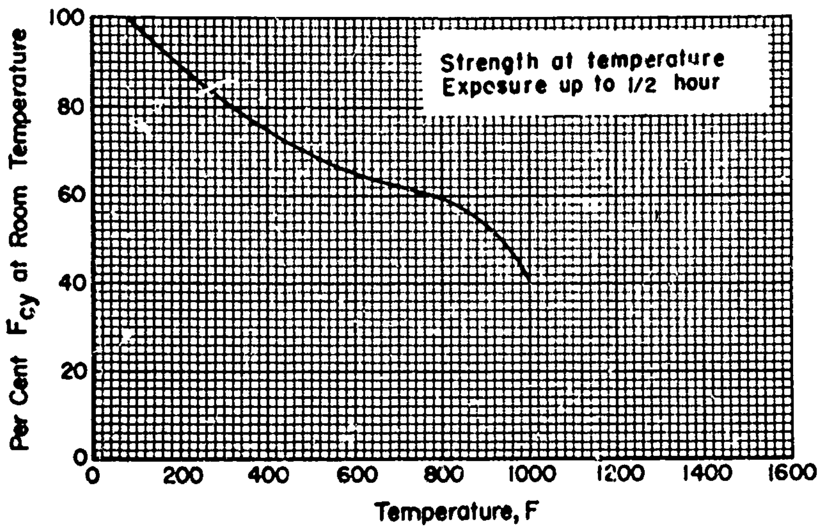

FIGURE 5-4.3.1-3. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY

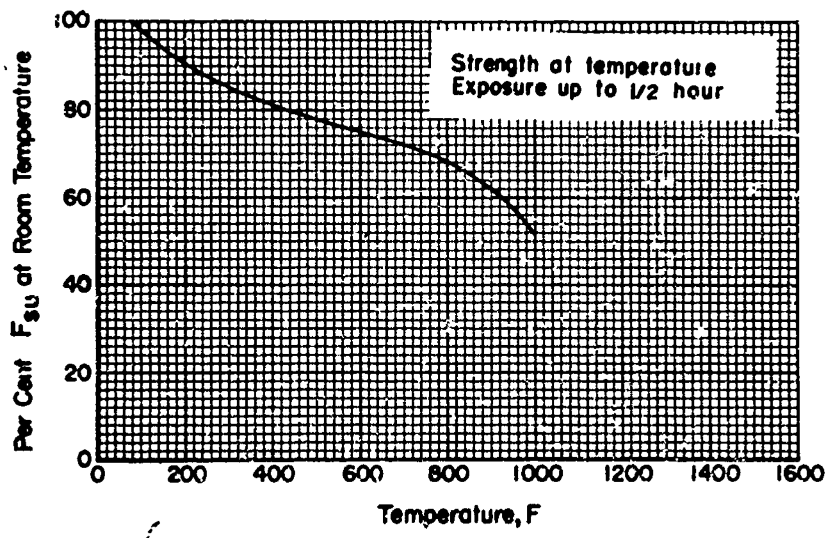

FIGURE 5-4.3.1-4. EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY

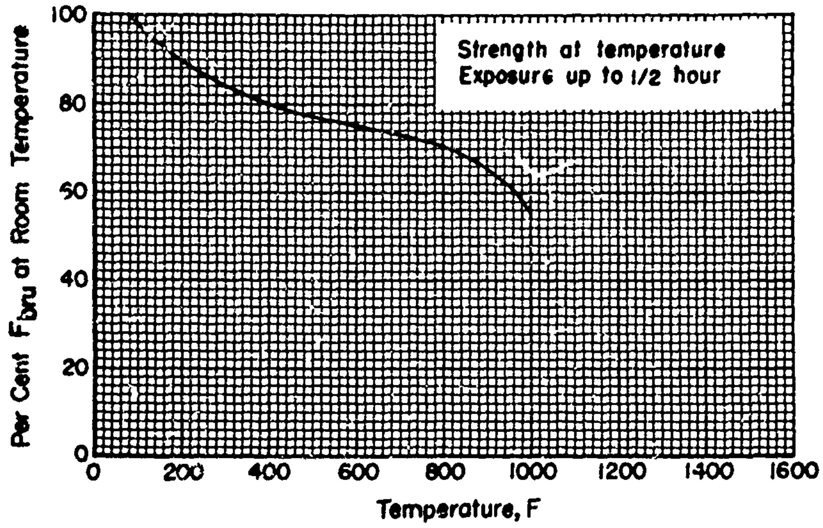

FIGURE 5-4.3.1-5. EFFECT OF TEMPERATURE ON THE ULTIMATE BEARING STRENGTH (F_{bru}) OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY

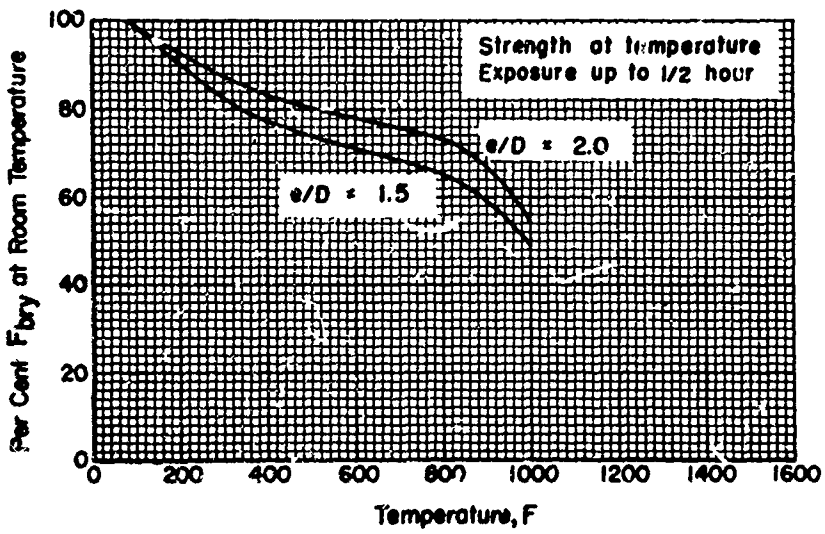

FIGURE 5-4.3.1-6. EFFECT OF TEMPERATURE ON THE BEARING YIELD STRENGTH (F_{bry}) OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY

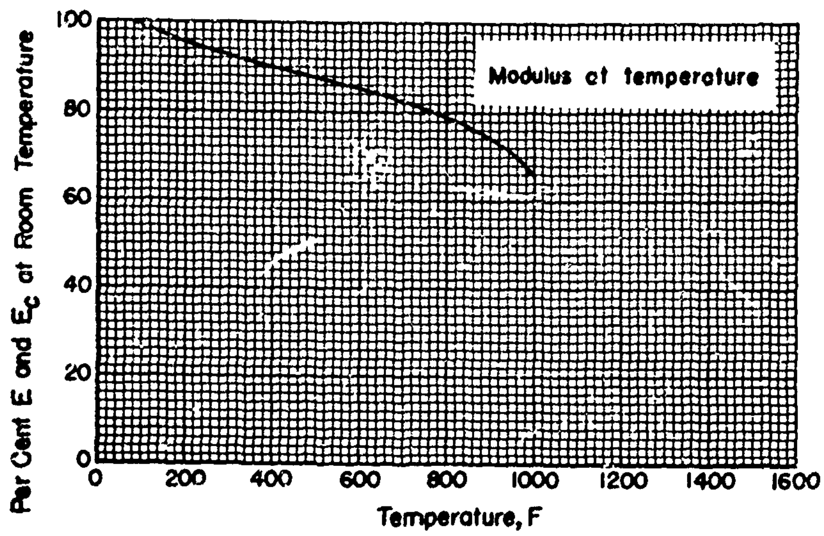

FIGURE 5-4.3.1-7. EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E AND E_c) OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY

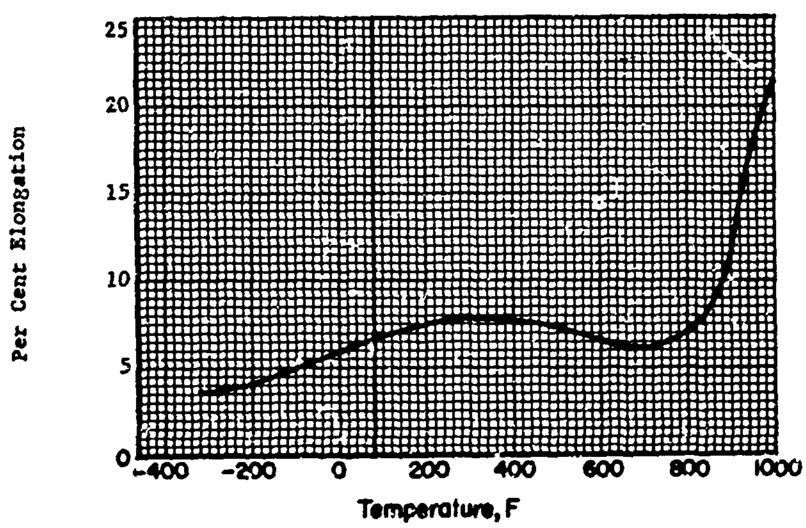

FIGURE 5-4.3.1-8. EFFECT OF TEMPERATURE ON THE ELONGATION OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY

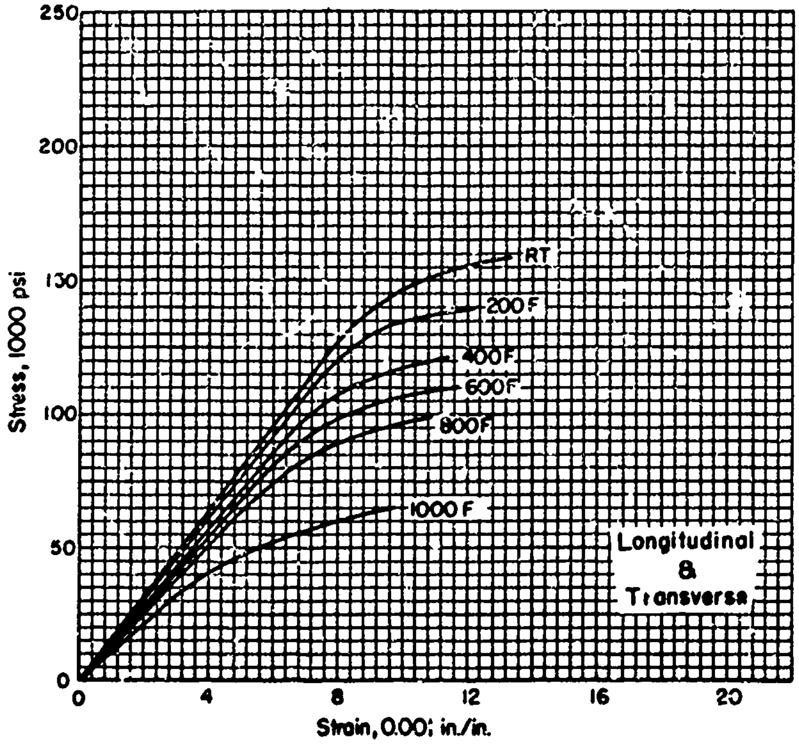

FIGURE 5-4.3.3-1. TYPICAL TENSILE STRESS-STRAIN CURVES FOR SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

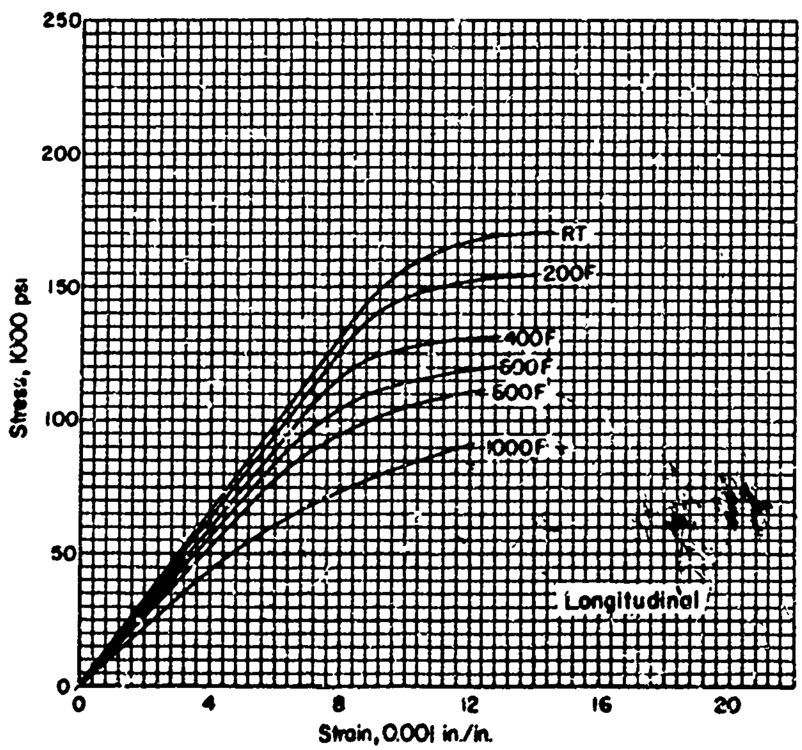

FIGURE 5-4.3.3-2. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

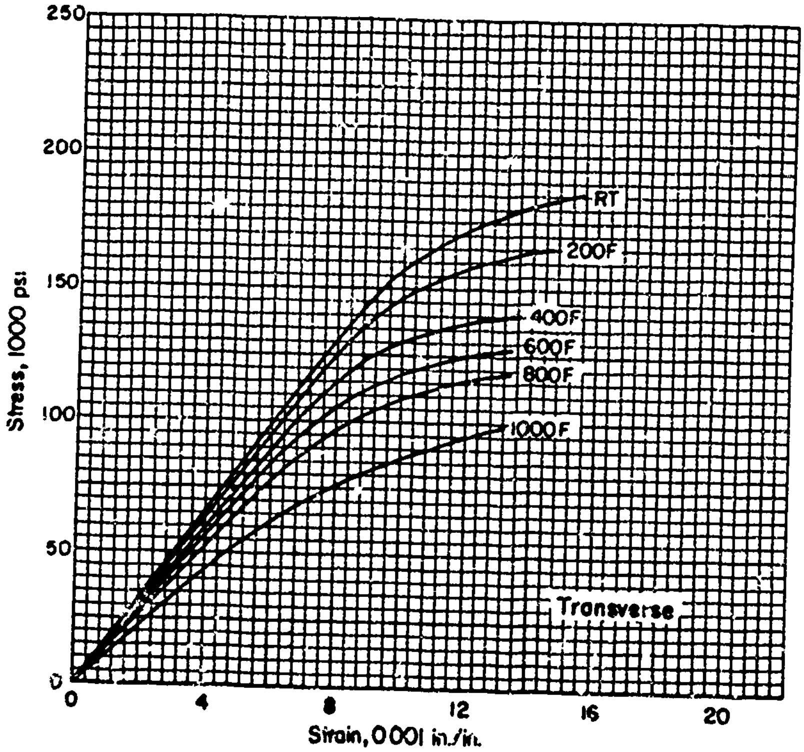

FIGURE 5-4.3.3-3. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

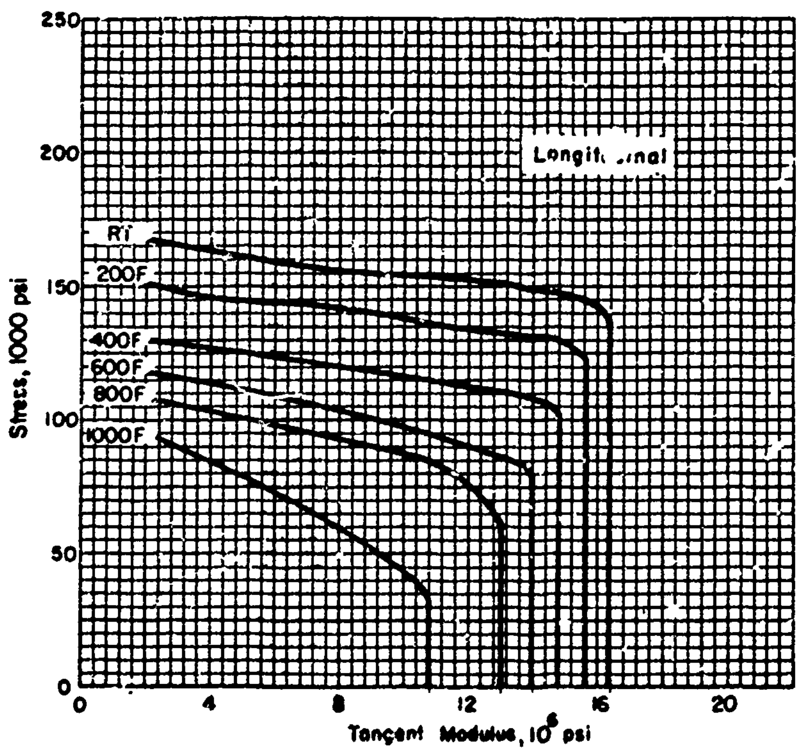

FIGURE 5-4.3.3-4. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

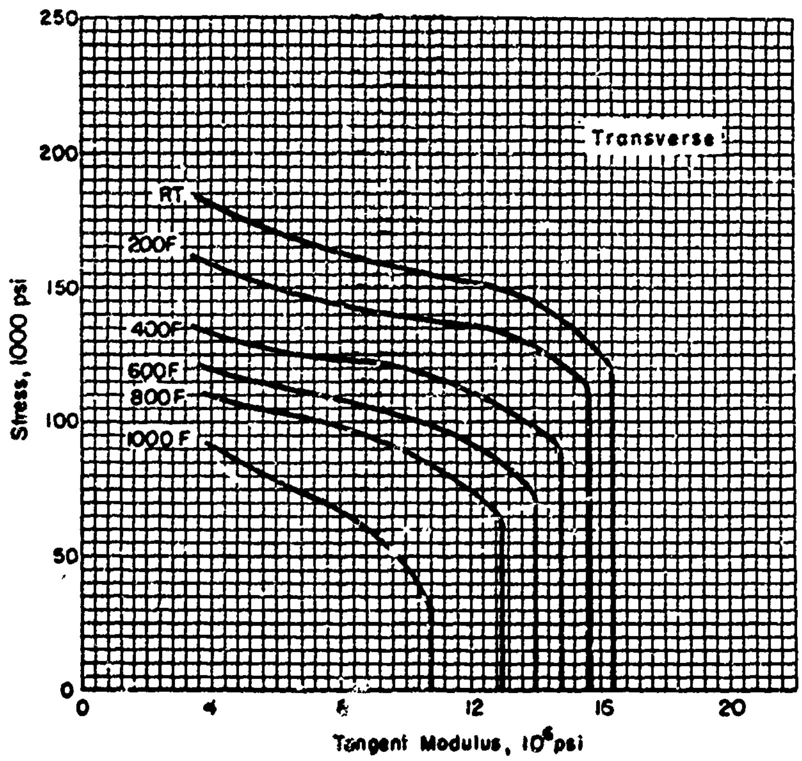

FIGURE 5-4.3.3-5. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

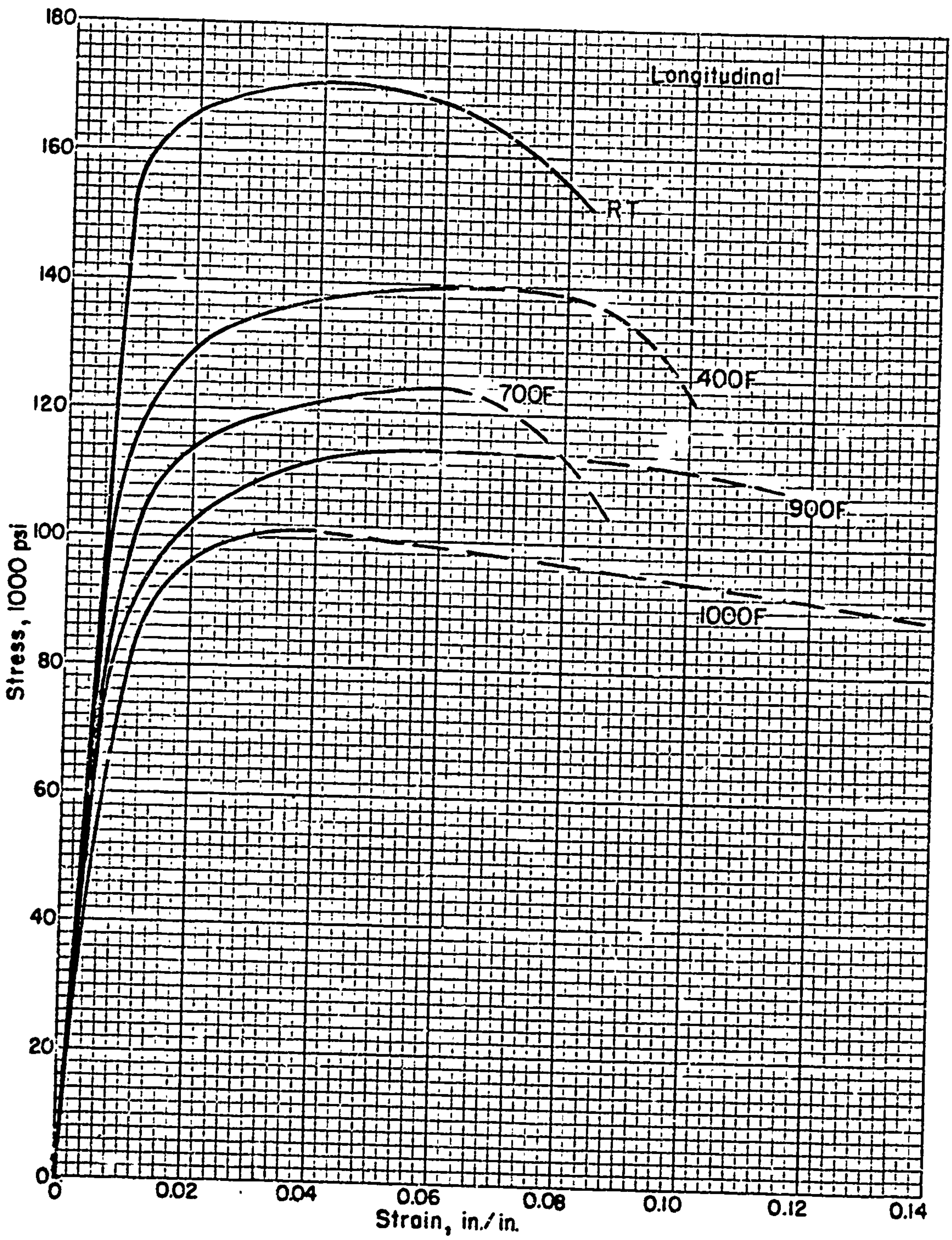

FIGURE 5-4.3.3-6. TYPICAL FULL-RANGE STRESS-STRAIN CURVES FOR SOLUTION-TREATED AND AGED Ti-6Al-4V AT ROOM AND ELEVATED TEMPERATURES(47)

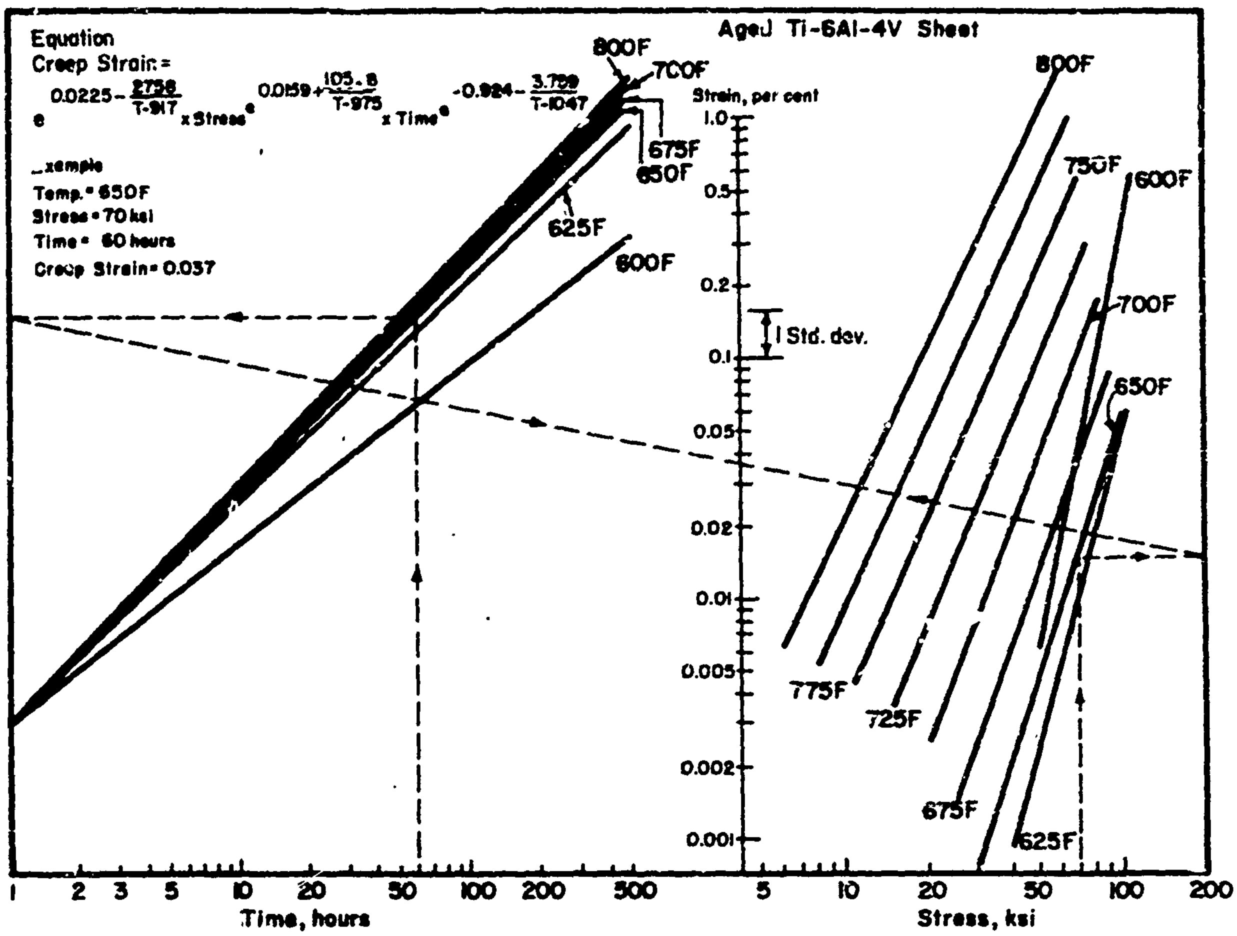

FIGURE 5-4.3.4-1. TYPICAL CREEP PROPERTIES OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SHEET

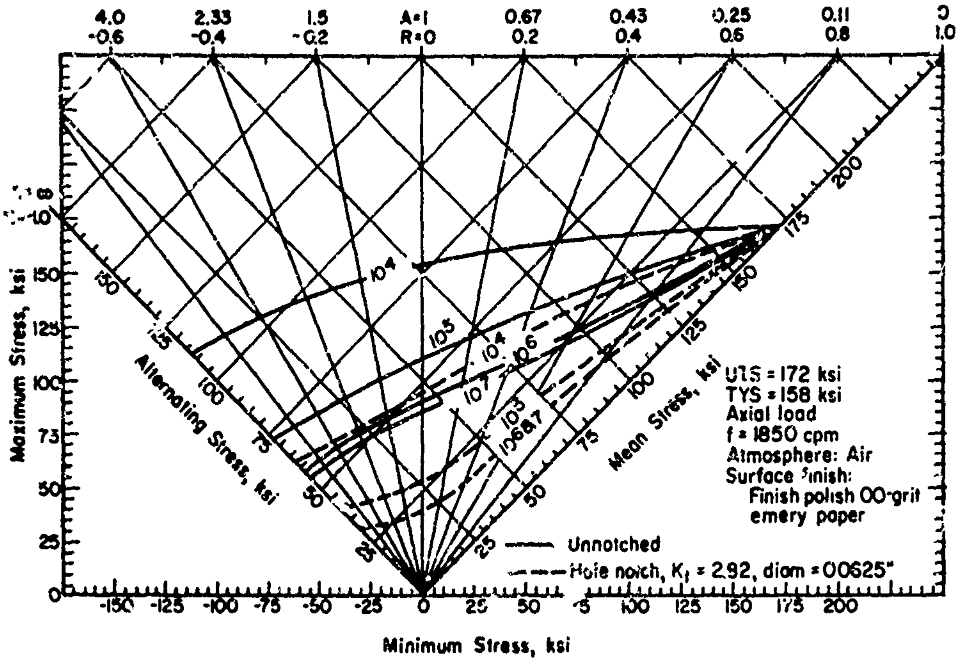

FIGURE 5-4.3.5-1. TYPICAL CONSTANT-LIFE DIAGRAM FOR FATIGUE BEHAVIOR OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SHEET AT ROOM TEMPERATURE(19)

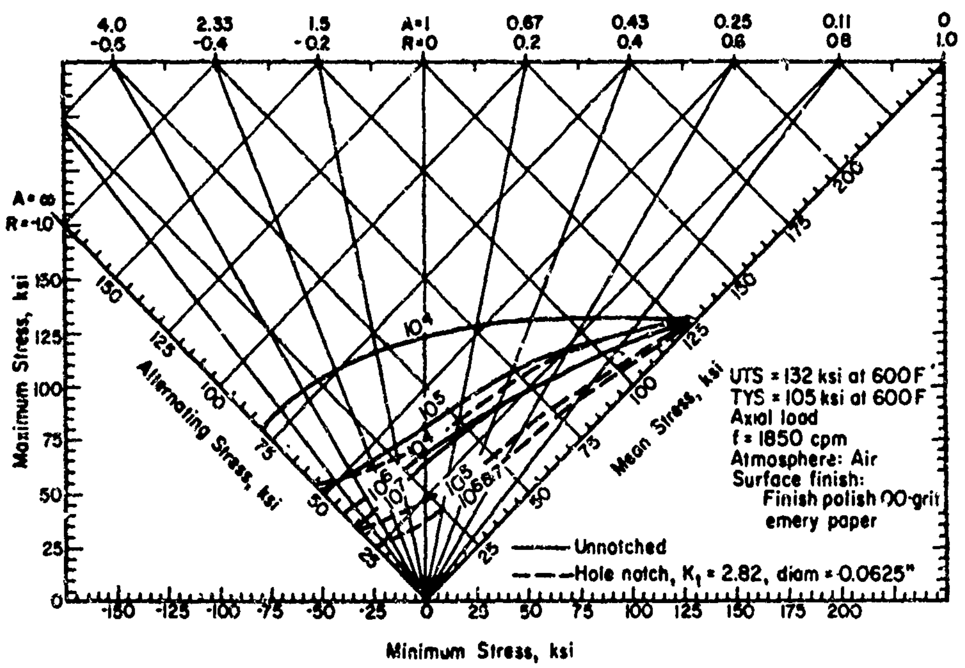

FIGURE 5-4.3.5-2. TYPICAL CONSTANT-LIFE DIAGRAM FOR FATIGUE BEHAVIOR OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SHEET AT 600 F(19)

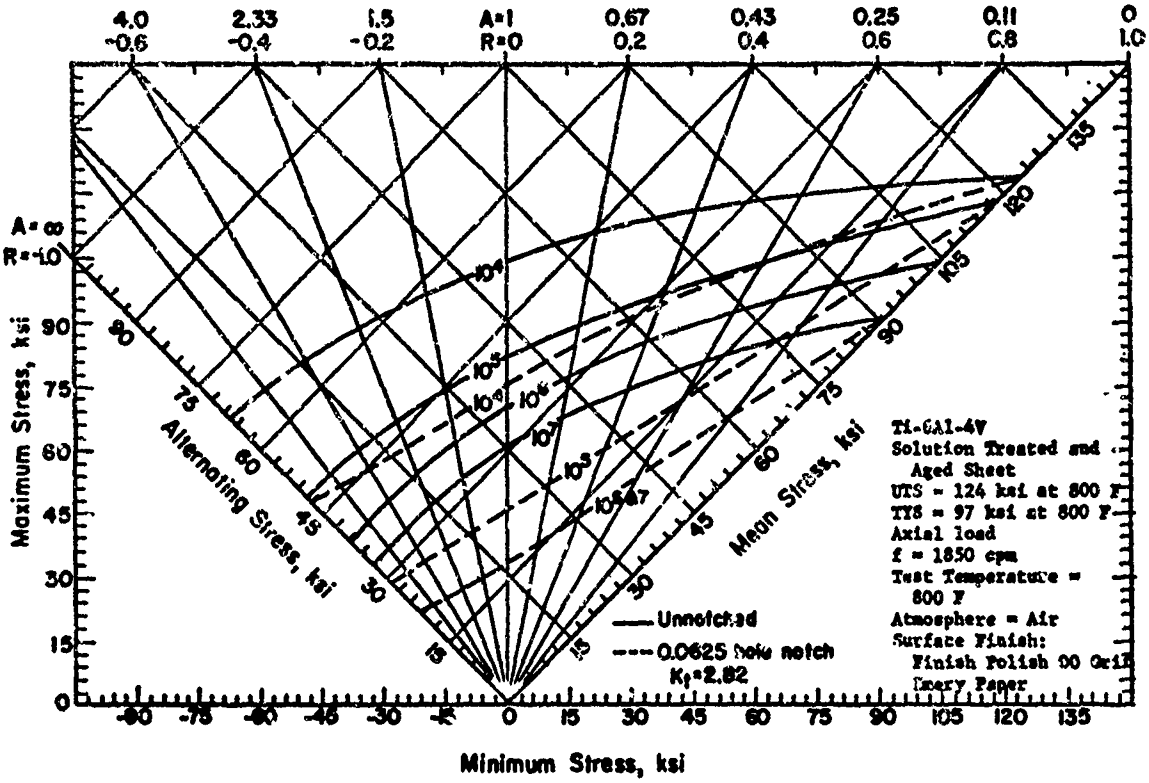

FIGURE 5-4.3.5-3. TYPICAL CONSTANT-LIFE DIAGRAM FOR FATIGUE BEHAVIOR OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SHEET AT 800 F (19)

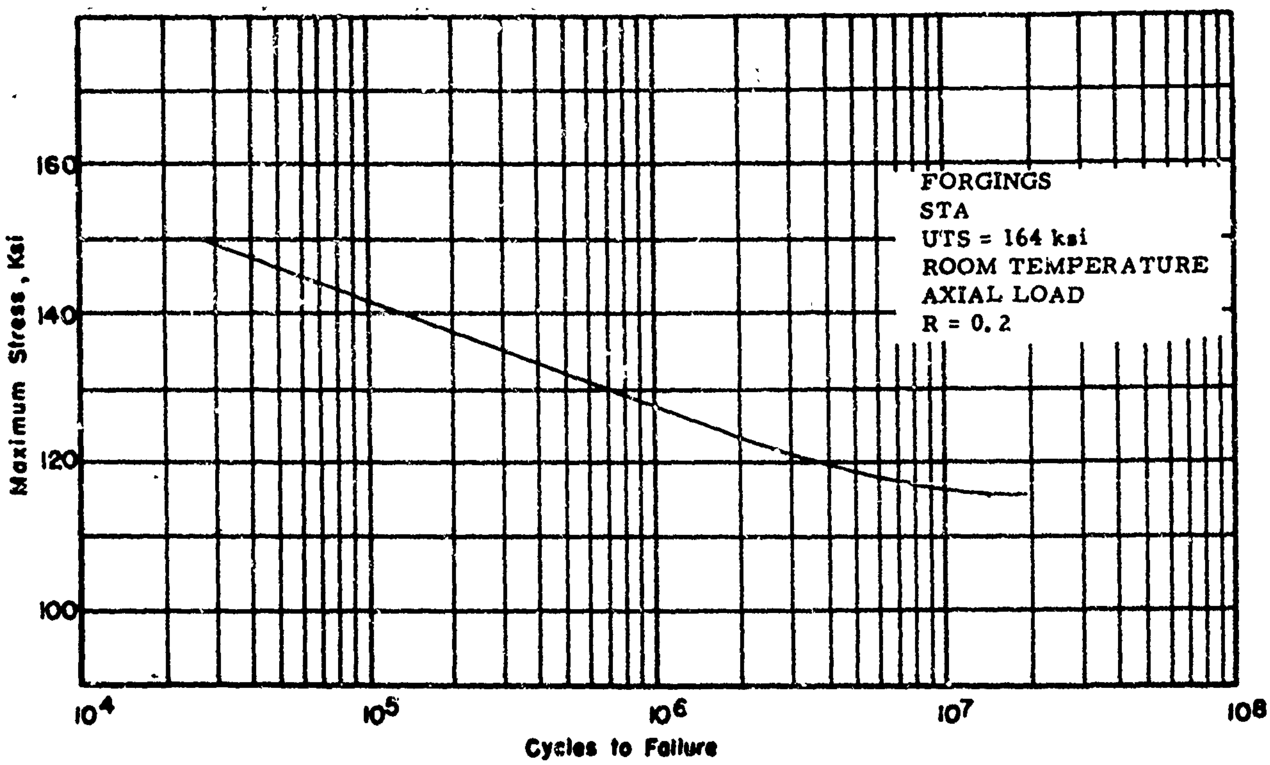

FIGURE 5-4.3.5.4. S-N DIAGRAM FOR UNNOTCHED SPECIMENS OF SOLUTION-TREATED AND AGED, FORGED Ti-6Al-4V TESTED AT AN R VALUE OF 0.2(71)

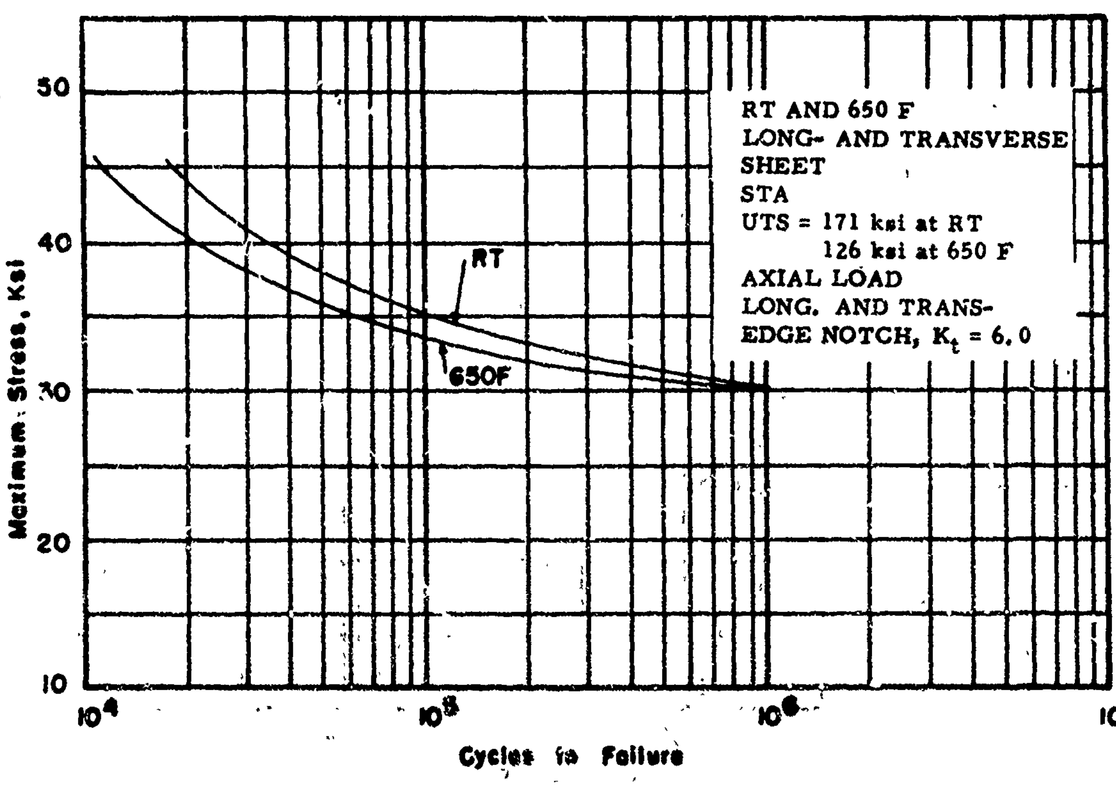

FIGURE 5-4.3.5-5. S-N DIAGRAM FOR EDGE-NOTCHED (K_t = 6, R = 0.010 IN) SPECIMENS OF SOLUTION-TREATED AND AGED Ti-6Al-4V ALLOY SUBJECTED TO A MEAN STRESS OF 25 KSI(28)

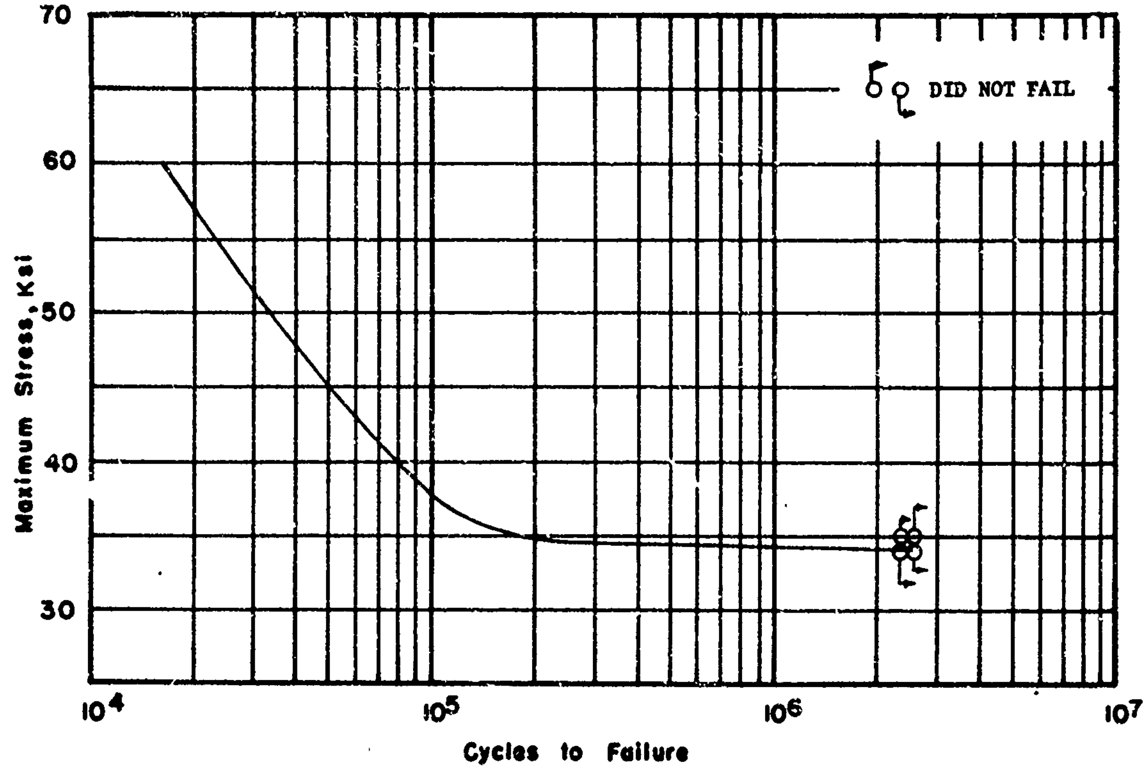

FIGURE 5-4.3.5-6. S-N DIAGRAM FOR NOTCHED (K_t = 2.58) SPECIMENS OF BETA-TREATED PLUS SOLUTION-TREATED AT 1725 F FOR 30 MIN, WATER QUENCHED AND AGED AT 1000 F FOR 4 HOURS AND AIR COOLED ANGLE EXTRUSIONS OF Ti-6Al-4V ALLOY(69)

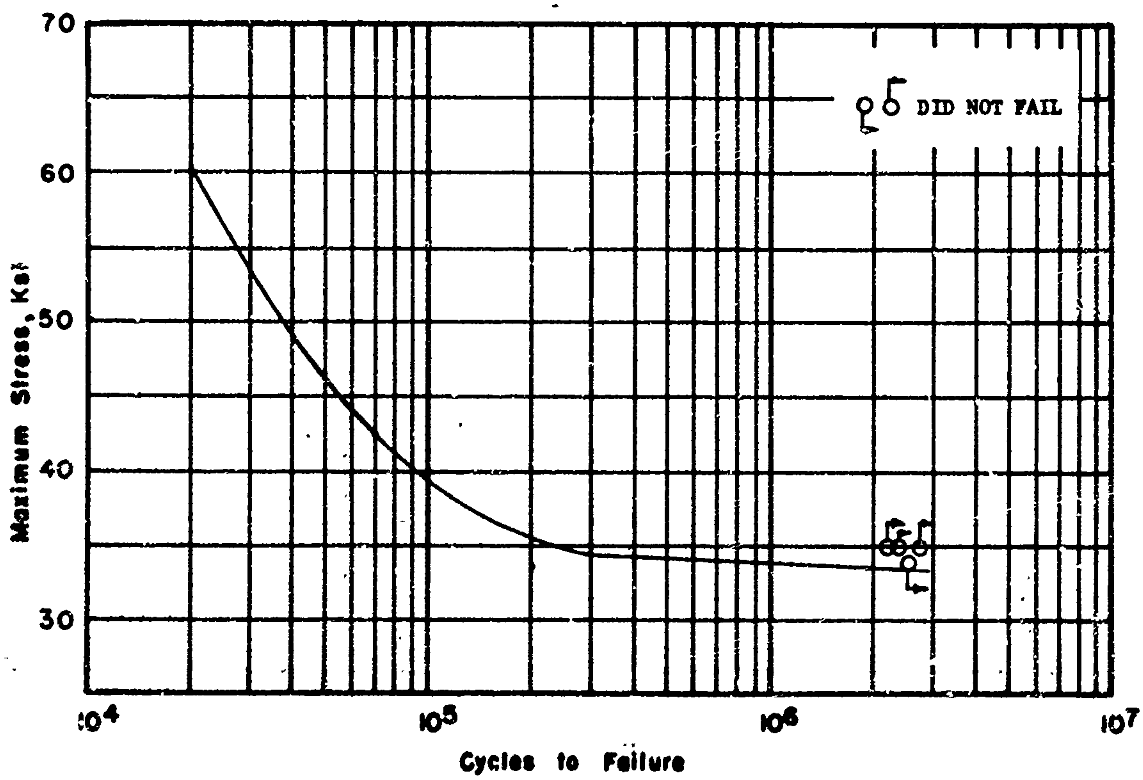

FIGURE 5-4.3.5-7. S-N DIAGRAM FOR NOTCHED (K_t = 2.58) SPECIMENS OF BETA-TREATED PLUS SOLUTION-TREATED AT 1725 F FOR 30 MIN, WATER QUENCHED AND AGED AT 1250 F FOR 4 HOURS AND AIR COOLED ANGLE EXTRUSION OF Ti-6Al-4V ALLOY(4)

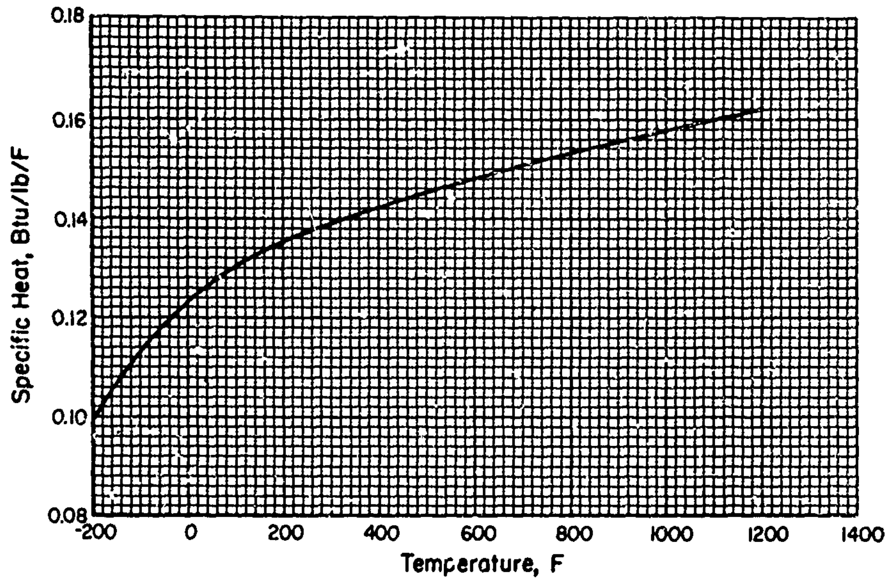

FIGURE 5-4.4-1. EFFECT OF TEMPERATURE ON THE SPECIFIC HEAT (C) OF Ti-6Al-4V(19)

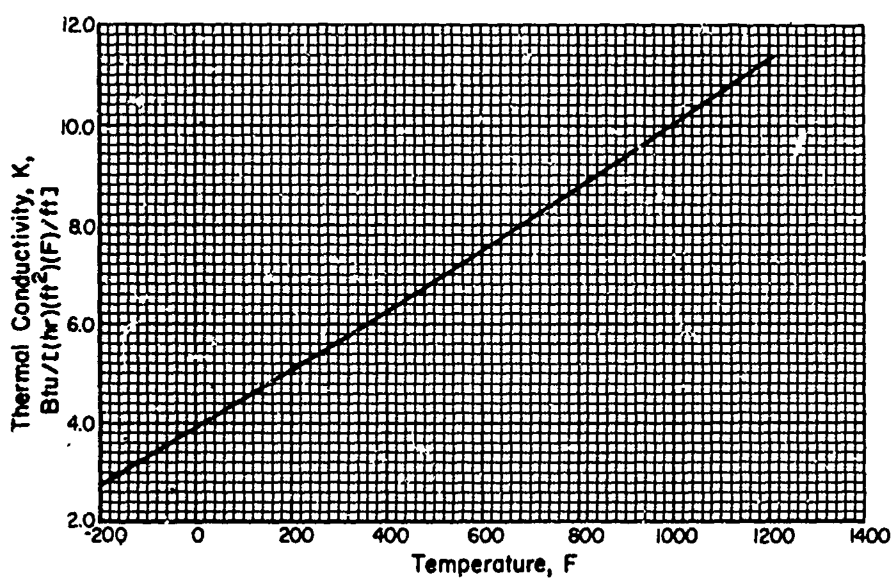

FIGURE 5-4.4-2. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY (K) OF Ti-6Al-4V(19)

Note: The curves on this page differ from corresponding curves in MIL-HDBK-5

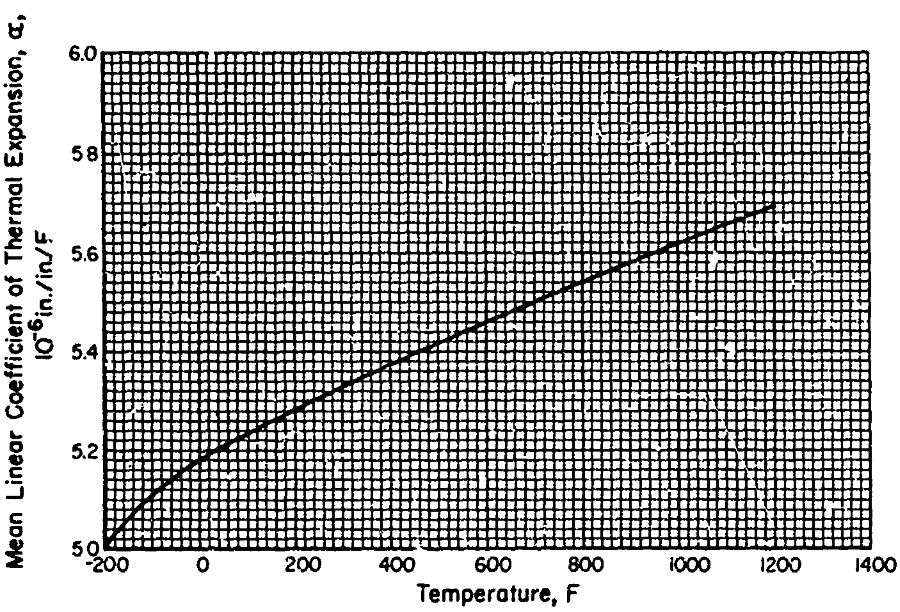

FIGURE 5-4.4-3. MEAN LINEAR COEFFICIENT OF THERMAL EXPANSION (α) OF Ti-6Al-4V BETWEEN ROOM TEMPERATURE AND THE INDICATED TEMPERATURE[19]

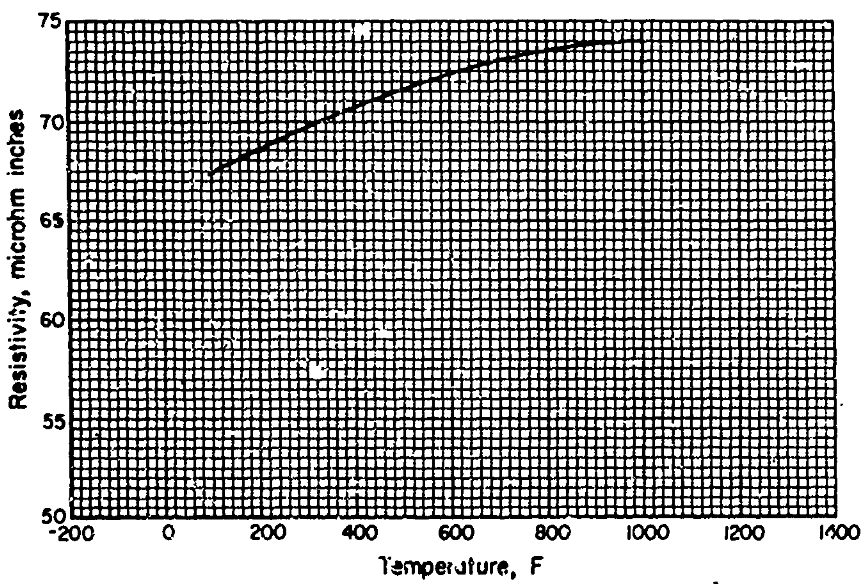

FIGURE 5-4.4-4. EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY (ρ) OF Ti-6Al-4V[1]

Note: The curves on this page differ from corresponding curves in MIL-HDBK-5

5-5 Titanium Alloy Ti-6Al-6V-2Sn

5-5.0 SPECIFICATIONS AND FORMS

This section covers titanium alloy Ti-6Al-6V-2Sn of the following specifications and forms:

Specification	Form
MIL-T-9046	Sheet, strip, and plate
MIL-7-9047	Bars and forgings
. . . . .	Extrusions
MIL-H-81200	Heat treatment, all forms

5-5.1 ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES

Table 5-5.1-1 summarizes the design mechanical properties of titanium alloy Ti-6Al-6V-2Sn sheet, strip, and plate at room temperature. Tentative properties for bar-forging products are summarized in Table 5-5.1-2. Tentative properties for extrusions are summarized in Table 5-5.1-3.

5-5.2 ENVIRONMENTAL EFFECTS FOR ANNEALED MATERIAL

5-5.2.1 Stress-Strain and Tangent-Modulus Curves

A typical full-range stress-strain diagram at room temperature is presented in Figure 5-5.2.1-1.

5-5.2.5 Fatigue Effects

Constant-life diagrams for fatigue behavior at room temperature are presented in Figures 5-5.2.5-1 through 5-5.2.5-3. A typical S-N diagram for notched extrusions is presented in Figure 5-5.2.5-4. A typical S-N diagram for unnotched and notched plate is presented in Figure 5-5.2.5-5.

5-5.3 ENVIRONMENTAL EFFECTS FOR SOLUTION-TREATED AND AGED MATERIAL

5-5.3.1 Elevated-Temperature Effects

The effect of temperature data are presented in Figures 5-5.3.1-1 through 5-5.3.1-2.

5-5.3.4 Creep Effects

Creep data are presented in Figures 5-5.3.4-1.

5-5.4 THERMOPHYSICAL EFFECTS

The effect of temperature on physical properties is displayed in Figures 5-5.4-1 through 5-5.4-4.

[redacted]

Alloy....................	MIL-T-9046 Type III Comp. E							
Form....................	Sheet, strip, and plate							
Condition....................	Annealed				Solution treated and aged			
Thickness or diameter, in....	<0.187 [b]		0.188 to 2.000	>2.000	≤0.187	0.188 to 1.500	1.501 to 2.500	2.501 to 4.000
Basis....................	A	B	S	S	S	S	S	S
Mechanical properties:								
F_{tu}, ksi....................	[illegible]	[illegible]	150	145	170	170	160	150
F_{ty}, ksi....................	145	[illegible]	140	135	160	160	150	140
F_{cy}, ksi								
L	[illegible]	[illegible]	[illegible]	[redacted]				
T	[illegible]	[illegible]	[illegible]					
F_{su}, ksi....................	[illegible]	[illegible]	[illegible]					
F_{bru}, ksi:								
(e/D = 1.5)....................	[illegible]	[illegible]	[illegible]					
(e/D = 2.0)....................	[illegible]	[illegible]	[illegible]					
F_{bry}, ksi:								
(e/D = 1.5)....................	[illegible]	[illegible]	[illegible]					
(e/D = 2.0)....................	[illegible]	[illegible]	[illegible]					
e, per cent:								
In 2 in....................	10L8T[a]	-	10L8T	8L6T	8L6T	8	6	6
In 4 D	-	-	-	-	-	-	-	-
E, 10^6 psi....................	15.0				16.5			
E_c, 10^6 psi....................	15.0				16.5			
G, 10^6 psi	5.7				6.3			
μ....................	0.32				0.32			
n....................	--							
ω, lb/in.^{3}....................	0.164							

Values in parentheses () are tentative values.

[a]For t <0.025 inch, elongation is 8L,6T. [b]Values in these columns are higher than in MIL-HDBK-5; the A values for F_{tu}, F_{ty}, and e are equal to minimums in the Revision F of MIL-T-9046, to be issued early 1967

[illegible] MECHANICAL PROPERTIES OF Ti-6Al-6V-2Sn [illegible]

Alloy	MIL-T-9047D	Type III	Composition C								
Form	Bars	Forgings	Bars and forgings								
Condition	Annealed		Solution-treated and aged per MIL-H-81200								
Thickness or diameter, in.	< 3		<0.5	>.5, < 1	> 1, < 1.5	> 1.5, < 2		>2, <3		>3, <4	
Width, in.	--		≤ 8	≤ 8	≤ 8	≤4	>4, ≤8	≤ 3,	> 3, ≤ 8	< 4	>4, ≤8
Basis	S	S	S	S	S	S	S	S	S	S	S
Mechanical properties:											
F_{tu}, ksi	140	140	170	170	170	170	160	155	150	150	145
F_{ty}, ksi	130	130	160	160	160	160	150	145	140	140	135
F_{cy}, ksi											
L	[illegible]	(132)	(163)	(163)	(163)	(163)	(153)	(148)	(142)	(142)	(137)
T	[illegible]	(140)	(172)	(172)	(172)	(172)	(162)	(156)	(151)	(151)	(145)
F_{su}, ksi	[illegible]	(91)	(110)	(110)	(110)	(110)	(104)	(100)	(97)	(97)	(94)
F_{bru}, ksi:											
(e/D = 1.5)	[illegible]	(211)	(256)	(256)	(256)	(256)	(241)	(234)	(226)	(226)	(219)
(e/D = 2.0)	[illegible]	(266)	(326)	(326)	(326)	(326)	(306)	(297)	(287)	(287)	(278)
F_{bry}, ksi:											
(e/D = 1.5)	[illegible]	(180)	(222)	(222)	(222)	(222)	(208)	(202)	(194)	(194)	(187)
(e/D = 2.0)	[illegible]	(212)	(262)	(262)	(262)	(262)	(246)	(238)	(229)	(229)	(221)
e, per cent:											
L	10	8	8[a]	8[b]	8	8[d]	8	8	8	8	8
T	10	8	6[a]	6	6[c]	6	6	6	6	6	6
E, 10^6 psi	15.0		16.5								
E_c, 10^6 psi	15.0		16.5								
G, 10^6 psi	5.7		6.3								
μ	0.32		0.32								
n											
ω, lb/in.^{3}			0.164								

Values in parentheses () are tentative values

[a] width > 1/2 [b] width > 1 [c] width > 1-1/2 [d] width > 2

Alloy	Ti-6Al-6V-2Sn		
Form	Extrusions[a]		
Condition	Annealed	Solution-treated and aged	
Thickness or diameter, in.	≤0.75	≤0.5	>0.5, ≤0.75
Basis	S[b]	S[b]	S[b]
Mechanical properties:			
F_{tu}, ksi	[illegible]	[illegible]	[illegible]
F_{ty}, ksi	[illegible]	[illegible]	[illegible]
F_{cy}, ksi	[illegible]	[illegible]	[illegible]
F_{su}, ksi	[illegible]	[illegible]	[illegible]
F_{bru}, ksi:			
(e/D = 1.5)	[illegible]	[illegible]	[illegible]
(e/D = 2.0)	[illegible]	[illegible]	[illegible]
F_{bry}, ksi:			
(e/D = 1.5)	[illegible]	[illegible]	[illegible]
(e/D = 2.0)	[illegible]	[illegible]	[illegible]
e, per cent:			
In 2 in.	[illegible]	[illegible]	[illegible]
In 4 D	[illegible]	[illegible]	[illegible]
E, 10^6 psi	15.0	16.5	
E_c, 10^6 psi	15.0	16.5	
G, 10^6 psi	5.7	6.3	
μ	0.32	0.32	
n	-	-	
w, lb/in.^{3}	0.164		

Values in parentheses () are tentative values.

a Properties applicable in longitudinal direction only.
b Producers' proposed specification values.
c Diameter of largest inscribed circle.

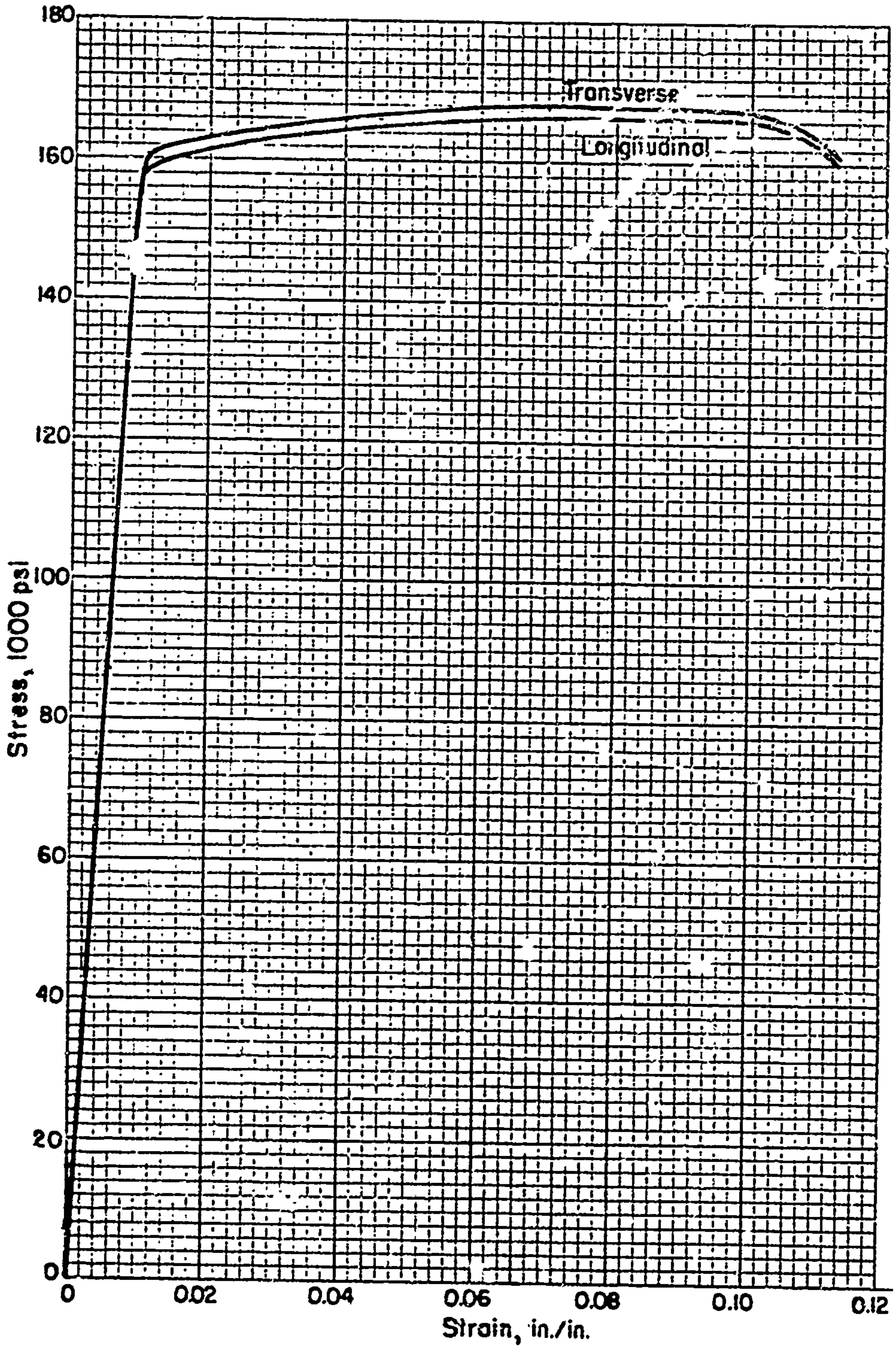

FIGURE 5-5.2.1-1. TYPICAL FULL-RANGE STRESS-STRAIN CURVES FOR ANNEALED Ti-6Al-6V-2Sn SHEET AT ROOM TEMPERATURE(47)

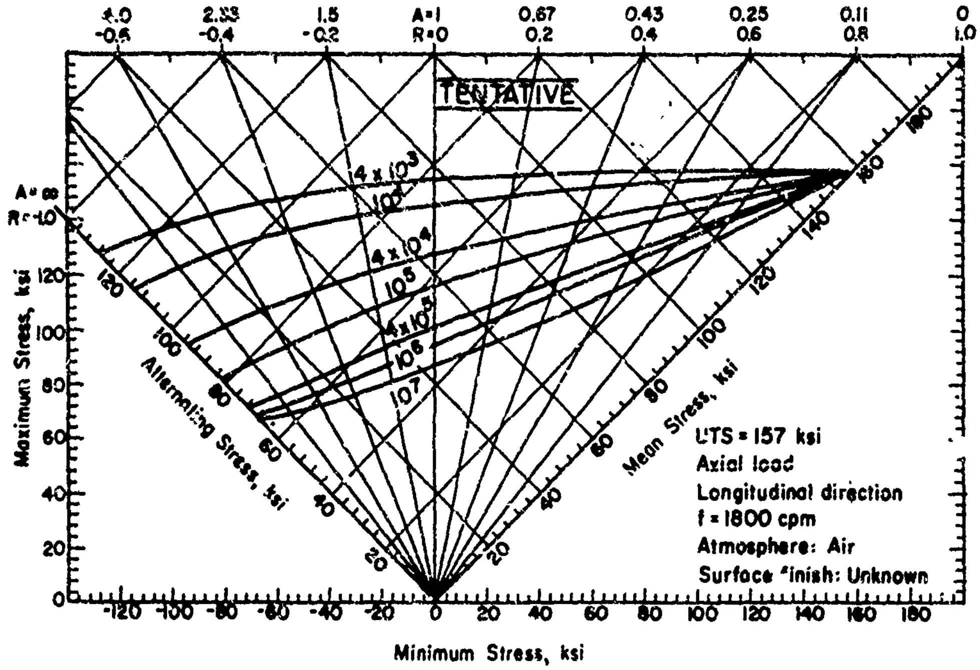

FIGURE 5-5.2.5-1. CONSTANT-LIFE FATIGUE DIAGRAM FOR Ti-6Al-6V-2.5Sn ANNEALED FORGINGS AT ROOM TEMPERATURE (UNNOTCHED)(40)

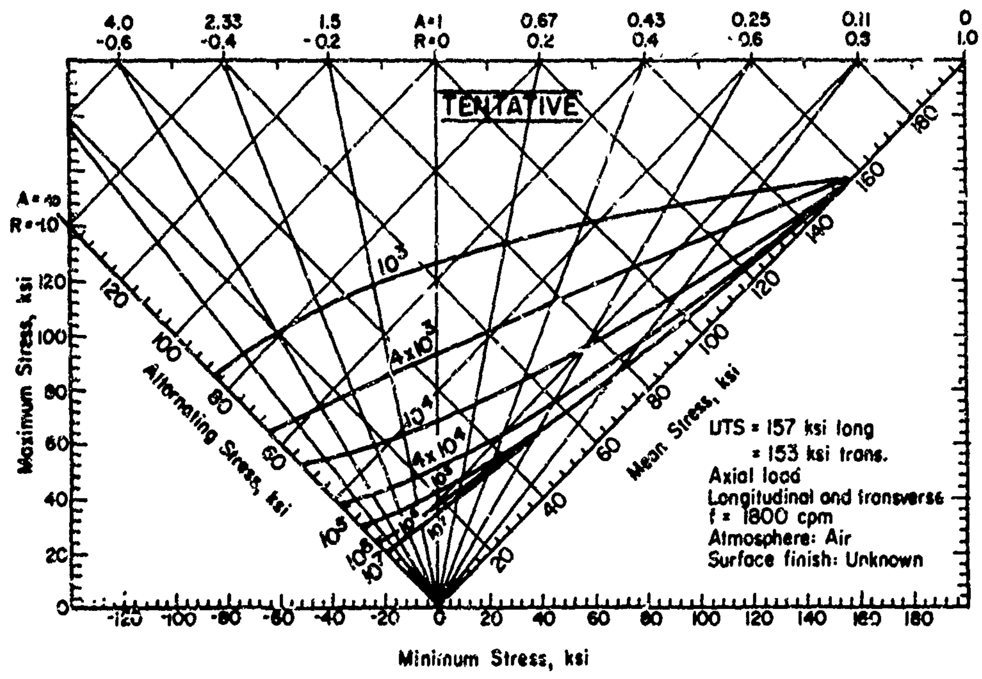

FIGURE 5-5.2.5-2. CONSTANT-LIFE FATIGUE DIAGRAM FOR Ti-6Al-6V-2.5Sn ANNEALED FORGINGS AT ROOM TEMPERATURE(40)

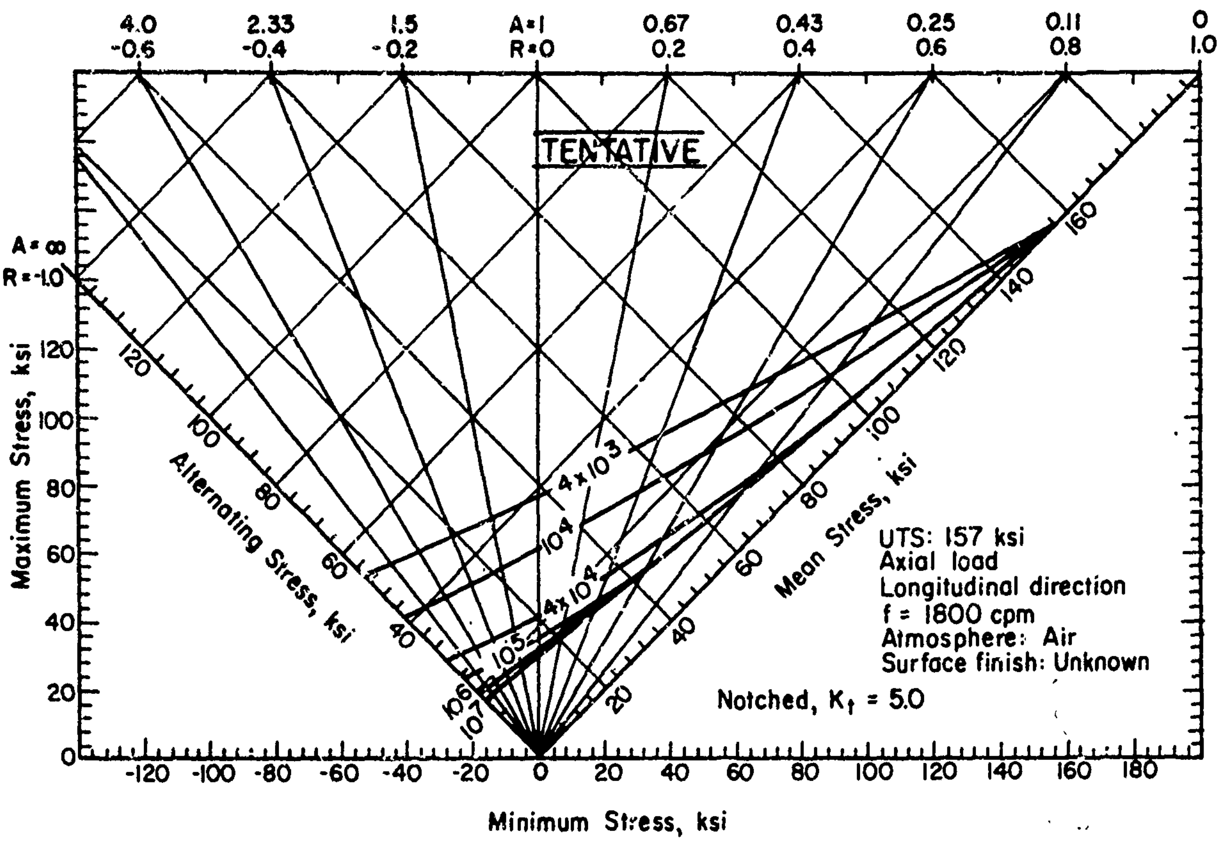

FIGURE 5-5.2.5-3. CONSTANT-LIFE FATIGUE DIAGRAM FOR Ti-6Al-6V-2.5Sn ANNEALED FORGINGS AT ROOM TEMPERATURE(40)

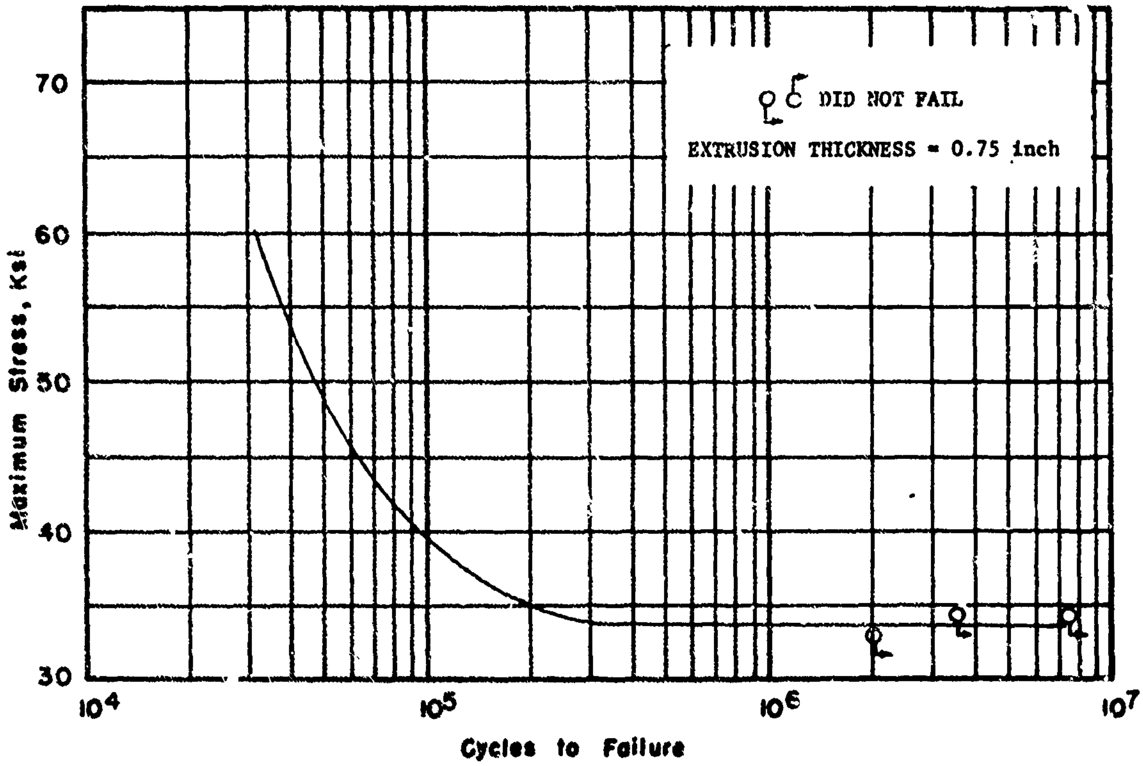

FIGURE 5-5.2.5-4. S-N DIAGRAM FOR NOTCHED (K_t = 2.58) SPECIMENS OF MILL ANNEALED Ti-6Al-6V-2Sn ALLOY TESTED AT AN R VALUE OF 0.06 (PERCENT)

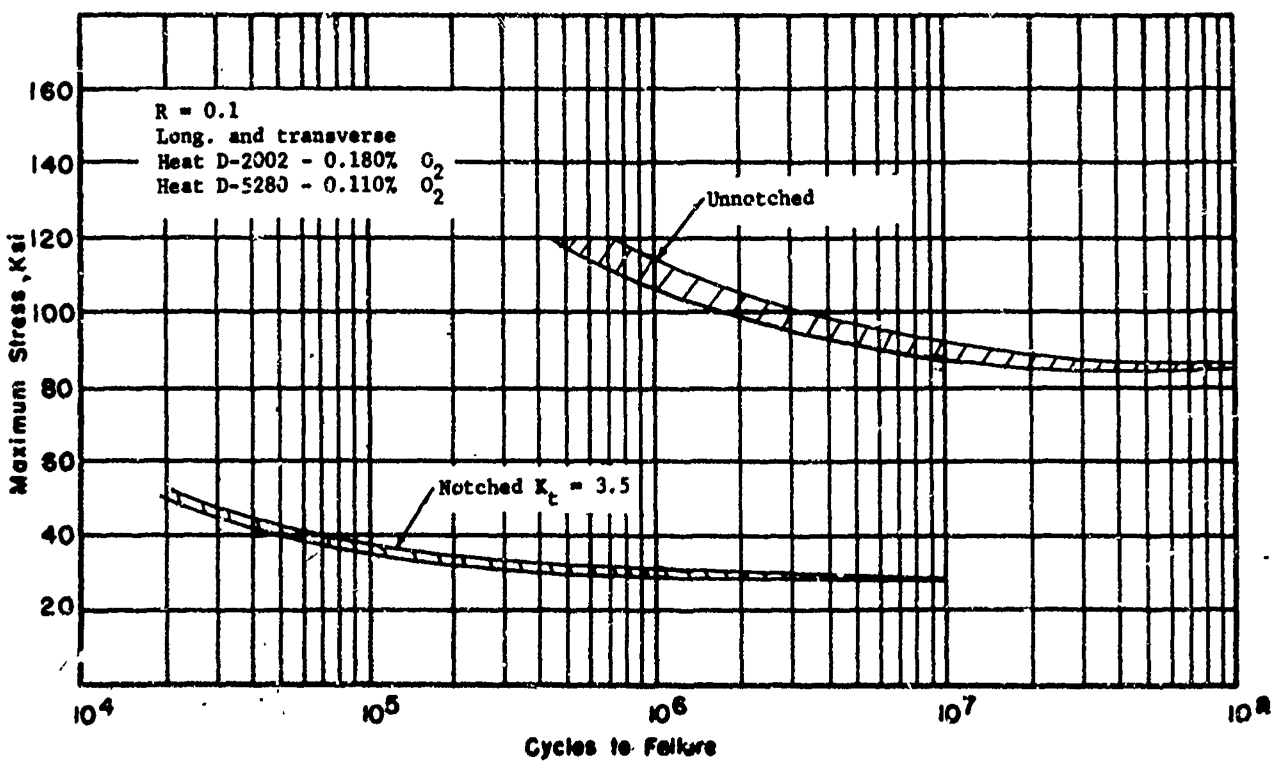

FIGURE 5-5.2.5-5. S-N DIAGRAM FOR UNNOTCHED AND NOTCHED (K_t = 3.5) SPECIMENS OF Ti-6Al-6V-2Sn PLATE (1-1/4 INCH THICK), HEATS D-2002 AND D-5280, ANNEALED AT 1300 F FOR 8 HOURS, AIR COOLED[72]

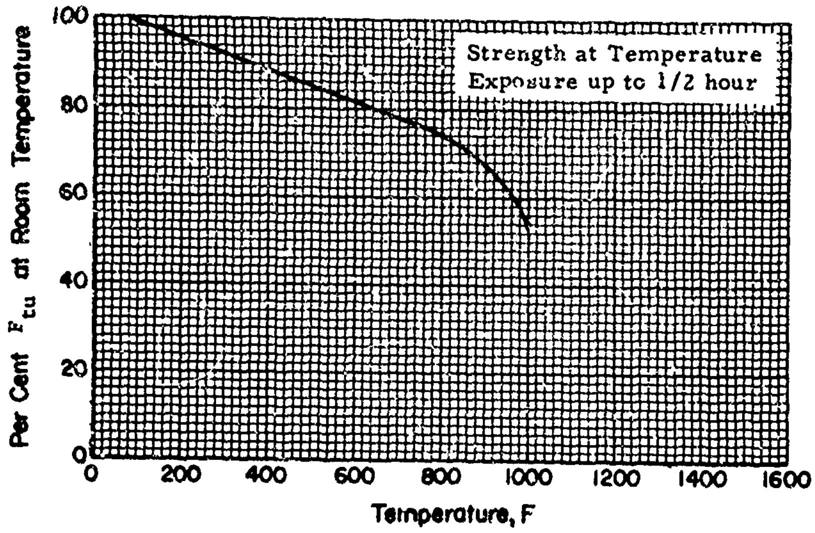

FIGURE 5-5.3.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn

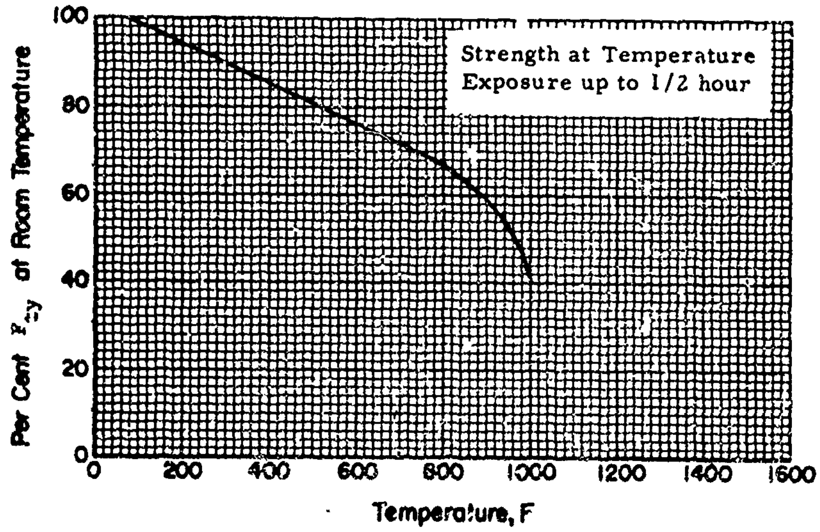

FIGURE 5-5.3.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn

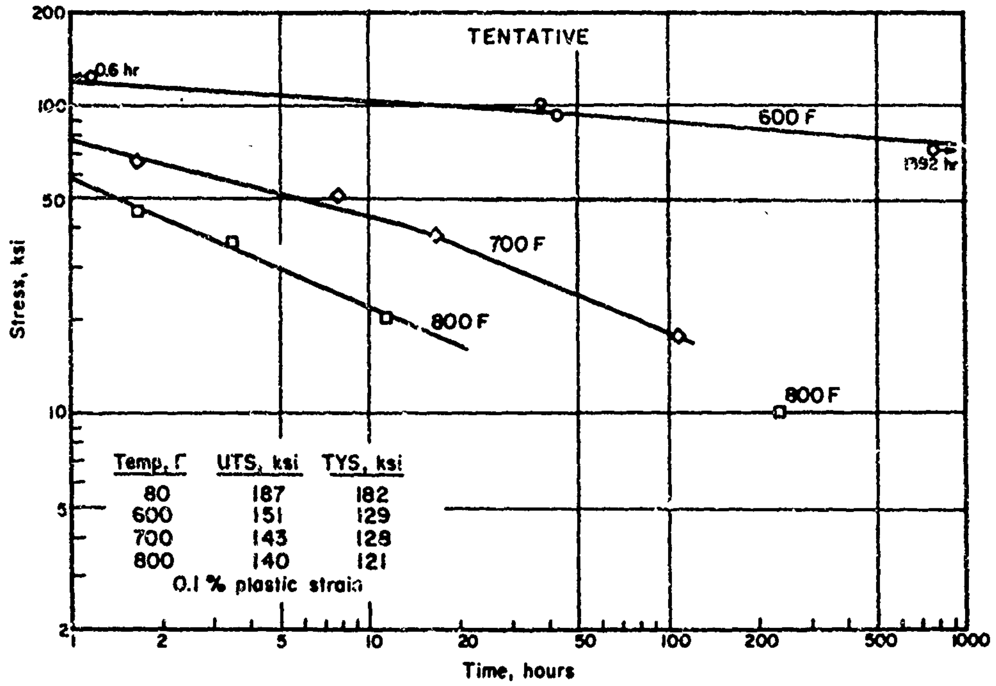

FIGURE 5-5.3.4-1. TYPICAL CREEP DATA FOR SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ALLOY BAR AT 600, 700, AND 800F[22]

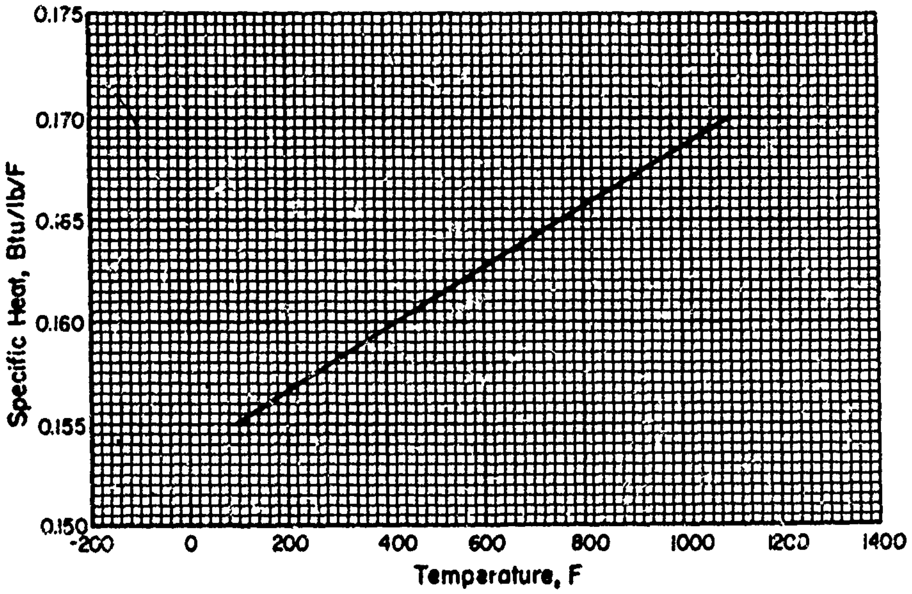

FIGURE 5-5.4-1. EFFECT OF TEMPERATURE ON THE SPECIFIC HEAT (C) OF Ti-6Al-6V-2Sn[17]

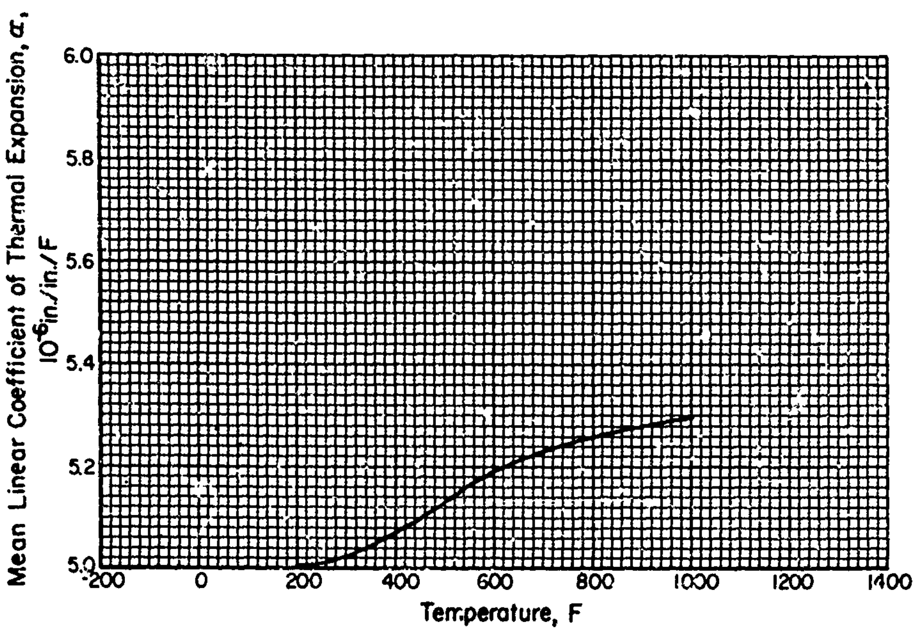

FIGURE 5-5.4-3. MEAN LINEAR COEFFICIENT OF THERMAL EXPANSION (α) OF Ti-6Al-6V-2Sn BETWEEN ROOM TEMPERATURE AND THE INDICATED TEMPERATURE(17)

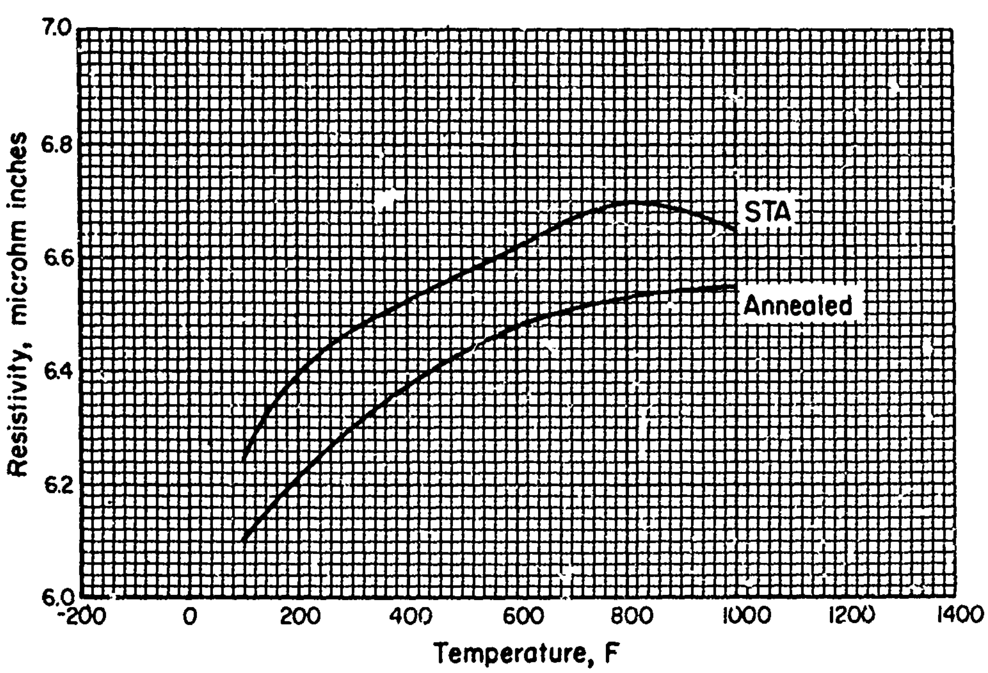

FIGURE 5-5.4-4. EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY (ρ) OF Ti-6Al-6V-2Sn(17)

5-6 Titanium Alloy Ti-13V-11Cr-3Al

5-6.0 SPECIFICATIONS AND FORMS

This section covers titanium alloy Ti-13V-11Cr-3Al of the following specifications and forms:

Specification	Form
MIL-T-9046	Sheet, strip, and plate
MIL-T-9047	Bars and forgings
MIL-H-81200	Heat treatment, all forms

5-6.1 ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES

Table 5-6.1-1 summarizes the design mechanical properties of titanium alloy Ti-13V-11Cr-3Al sheet, strip, and plate at room temperature. Properties for bar and forging products are summarized in Table 5-6.1-2.

5-6.2 ENVIRONMENTAL EFFECTS FOR ANNEALED MATERIAL

5-6.2.1 Elevated-Temperature Effects

The effect of temperature data are presented in Figures 5-6.2.1-1 through 5-6.2.1-7.

5-6.2.2 Exposure Effects

100-hour exposure at 800 F results in aging of this alloy.

5-6.2.3 Stress-Strain and Tangent-Modulus Curves

Typical stress-strain curves for room and elevated temperatures are presented in Figures 5-6.2.3-1 through 5-6.2.3-4. Typical compressive tangent-modulus curves are presented in Figures 5-6.2.3-5 and 5-6.2.3-6.

5-6.3.3 Stress-Strain and Tangent Modulus Curves

Typical tensile and compressive stress-strain curves for room and elevated temperatures are presented in Figures 5-6.3.3-1 and 5-6.3.3-2. Typical compressive tangent-modulus curves are presented in Figure 5-6.3.3-3.

5-6.3.5 Fatigue Effects

Constant-life diagrams for fatigue behavior at room and elevated temperatures are presented in Figures 5-6.3.5-1 through 5-6.3.5-3.

5-6.4 THERMOPHYSICAL EFFECTS

The effect of temperature on physical properties is displayed in Figures 5-6.4-1 through 5-6.4-4.

5-6.2.5 Fatigue Effects

Constant-life diagrams for fatigue behavior at room and elevated temperatures are presented in Figures 5-6.2.5-1 through 5-6.2.5-3.

5-6.3 ENVIRONMENTAL EFFECTS FOR SOLUTION-TREATED AND AGED MATERIAL

5-6.3.1 Elevated-Temperature Effects

Data on the effect of temperature are presented in Figures 5-6.3.1-1 through 5-6.3.1-7.

5-6.3.2 Exposure Effect

Prolonged exposure at 550 F has a minor strengthening (aging) effect accompanied by a decrease in elongation at room temperature.

TABLE 5.6.1.1. ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES OF Ti-13V-11Cr-3Al SHEET, STRIP, AND PLATE

Alloy	MIL-T-9046 Type IV		
Form	Sheet, strip, and plate		
Condition	Annealed		Solution treated and aged
Thickness or diameter, in.	<0.050	≥0.050	<0.250
Basis	S[c]	S	S
Mechanical properties:			
F_{tu}, ksi	[illegible]	125	170
F_{ty}, ksi	[illegible]	120	160
F_{cy}, ksi	--	120	162
F_{su}, ksi	--	92	105
F_{bru}, ksi:			
(e/D = 1.5)	--	207	248
(e/D = 2.0)	--	270	313
F_{bry}, ksi:			
(e/D = 1.5)	--	169	217
(e/D = 2.0)	--	200	247
e, per cent:		200	247
In 2 in.	[redacted]	10	b4
In 4 D	--	--	--
E, 10^6 psi	14.5		15.5
E_c, 10^6 psi	15.5		16.5
G, 10^6 psi	5.7		6.1
μ	0.32		0.32
η	--		
w, lb/in.^{3}	0.174		

a Thickness 0.025 inch and over.
b For t<0.025 inch, e = 3.
c Per revision F to be issued early 1967.

TABLE 5-6.1-2. ROOM TEMPERATURE DESIGN MECHANICAL PROPERTIES FOR Ti-13V-11Cr-3Al BARS AND FORGINGS

Alloy	MIL-T-9047D Type IV Composition A		
Form	Bars and forgings		
Condition	Annealed	Solution-treated and aged per MIL-H-81200	
Thickness or diameter, in.	< 3	≤ 2[a]	> 2, ≤ 4[a]
Basis	S	S	S
Mechanical properties:			
F_{tu}, ksi	125	170	170
F_{ty}, ksi	120	160	160
F_{cy}, ksi	(120)	(142)	(142)
F_{su}, ksi	(98)	(105)	(105)
F_{bru}, ksi:			
(e/D = 1.5)	(207)	(266)	(266)
(e/D = 2.0)	(270)	(313)	(313)
F_{bry}, ksi:			
(e/D = 1.5)	(180)	(217)	(190)
(e/D = 2.0)	(208)	(247)	[illegible]
e, per cent:			
L	10	6	2
T	10	—	—
E, 10^6 psi	14.5		15.5
E_c, 10^6 psi	--		--
G, 10^6 psi	--		--
μ	--		--
n	--		--
ω, lb/in.^{3}	0.174		0.174

Values in parentheses () are tentative values

[a] Width ≤ 8

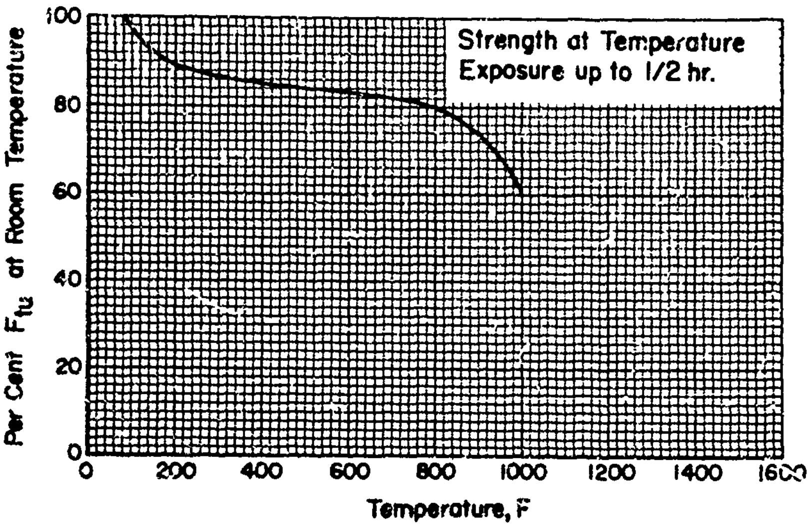

FIGURE 5-6.2.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET

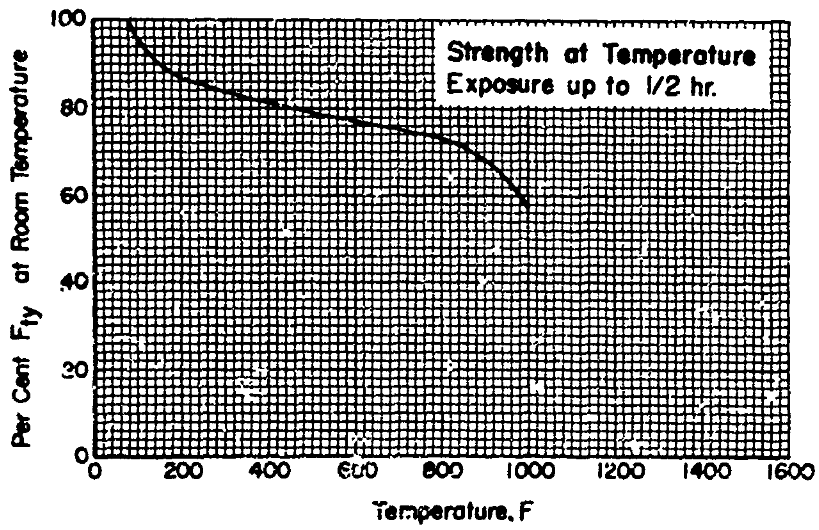

FIGURE 5-6.2.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET

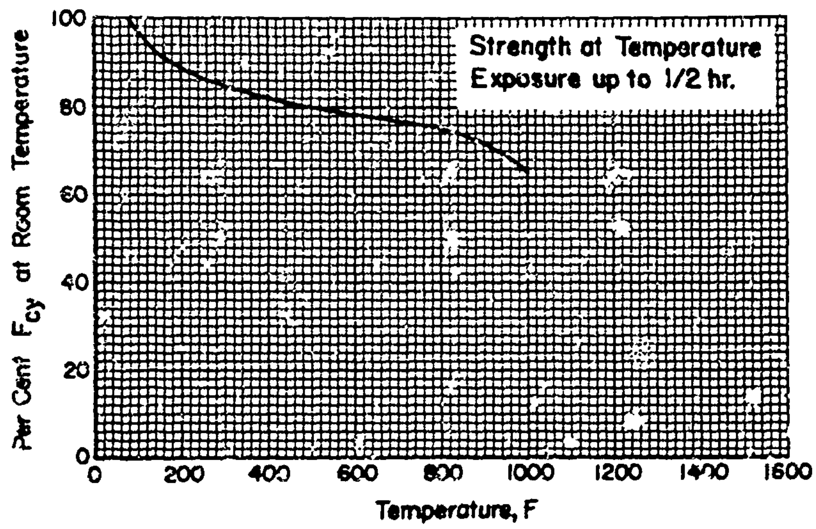

FIGURE 5-6.2.1-3. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF ANNEALED Ti-13V-11Cr 3Al ALLOY SHEET

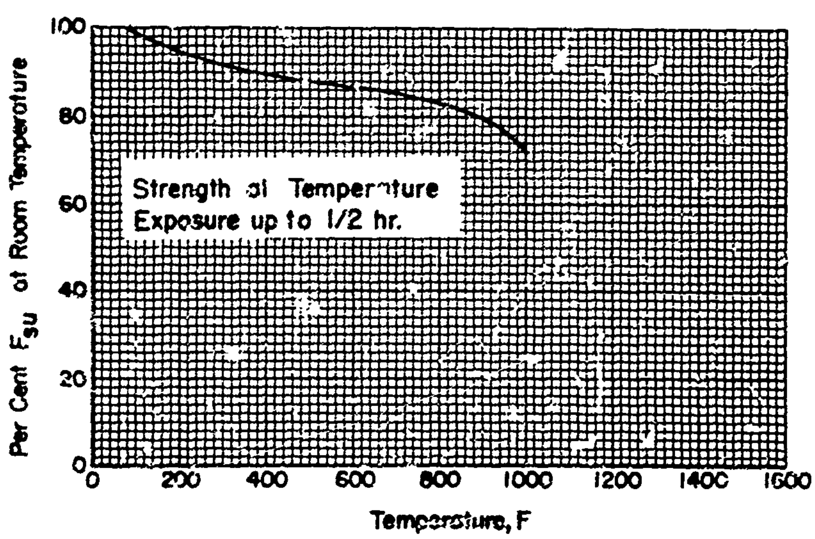

FIGURE 5-6.2.1-4. EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET

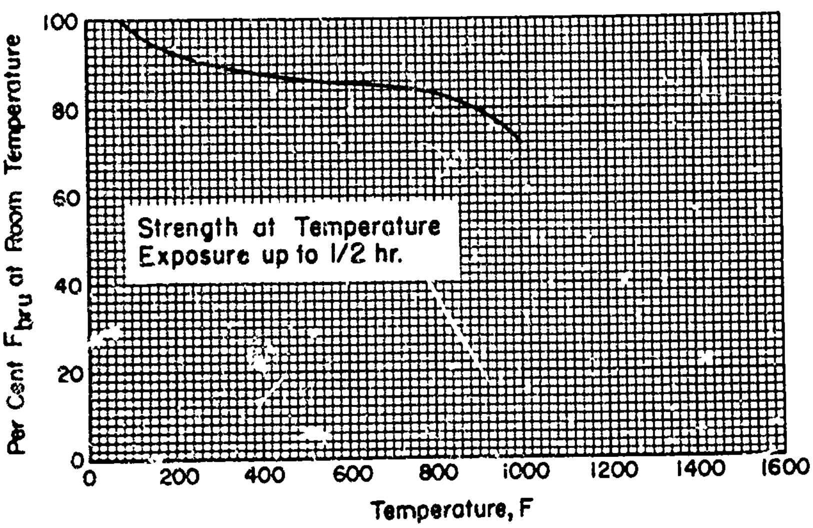

FIGURE 5-6.2.1-5. EFFECT OF TEMPERATURE ON THE ULTIMATE BEARING STRENGTH (F_{bru}) OF ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET

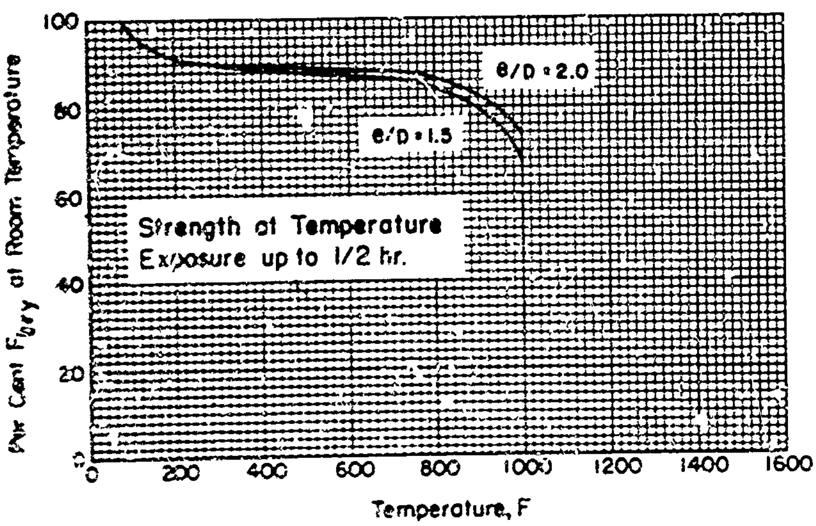

FIGURE 5-6.2.1-6. EFFECT OF TEMPERATURE ON THE BEARING YIELD STRENGTH (F_{bry}) OF ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET

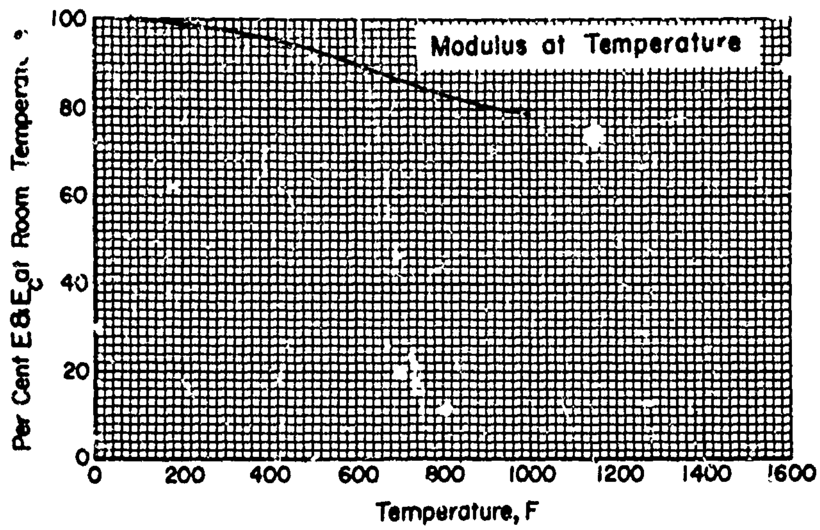

FIGURE 5-6.2.1-7. EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E AND E_c) OF ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET

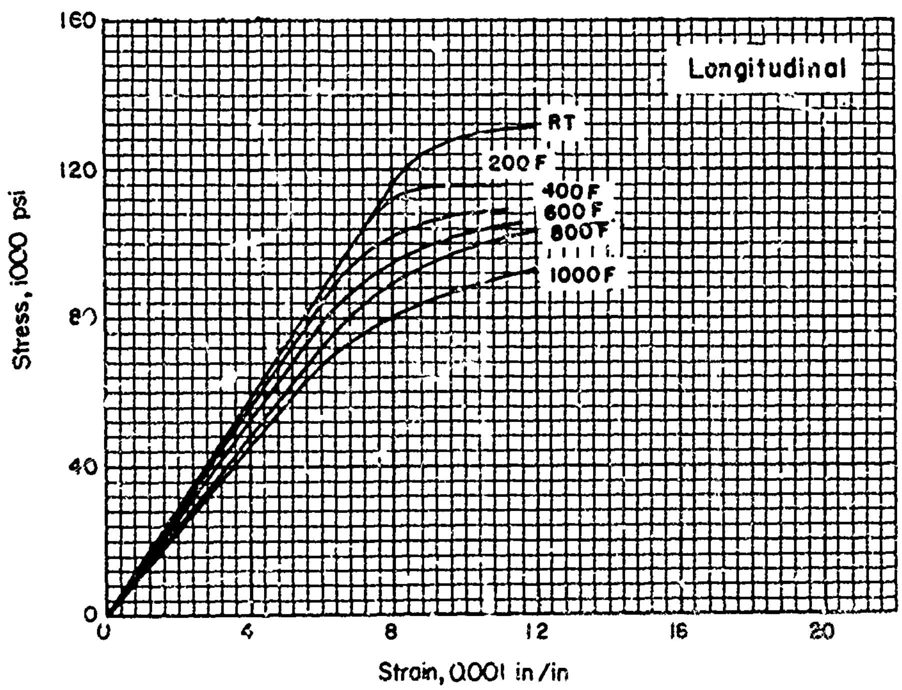

FIGURE 5-6.2.3-1. TYPICAL TENSILE STRESS-STRAIN CURVES FOR ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

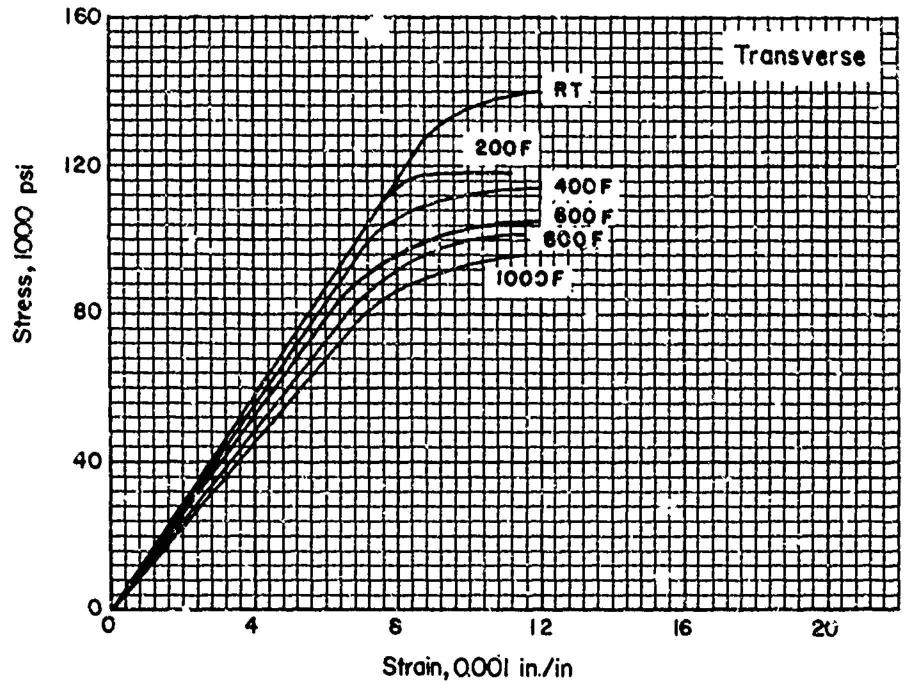

FIGURE 5-6.2.3-2. TYPICAL TENSILE STRESS-STRAIN CURVES FOR ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

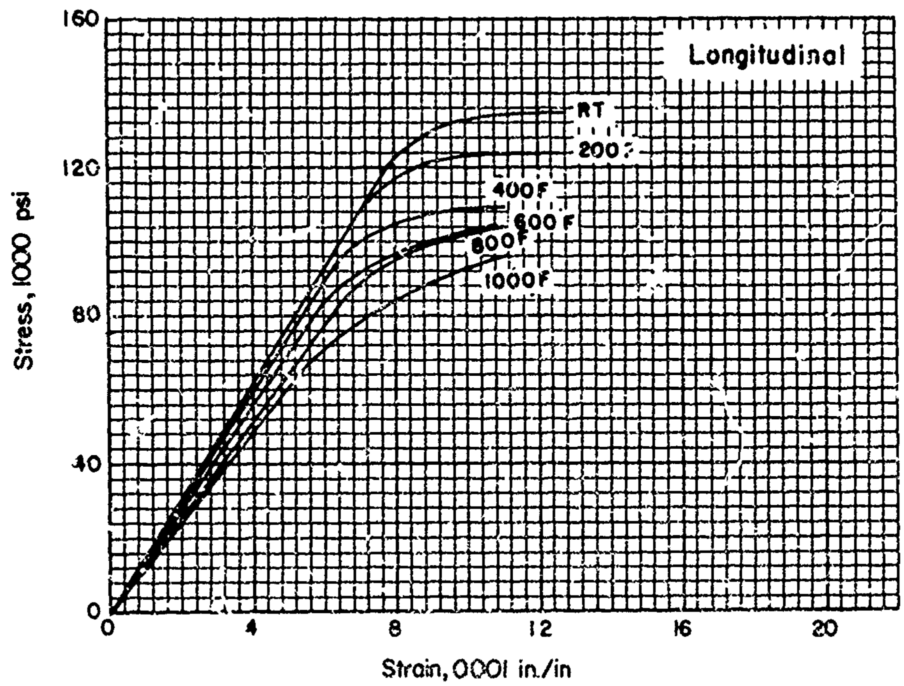

FIGURE 5-6.2.3-3. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

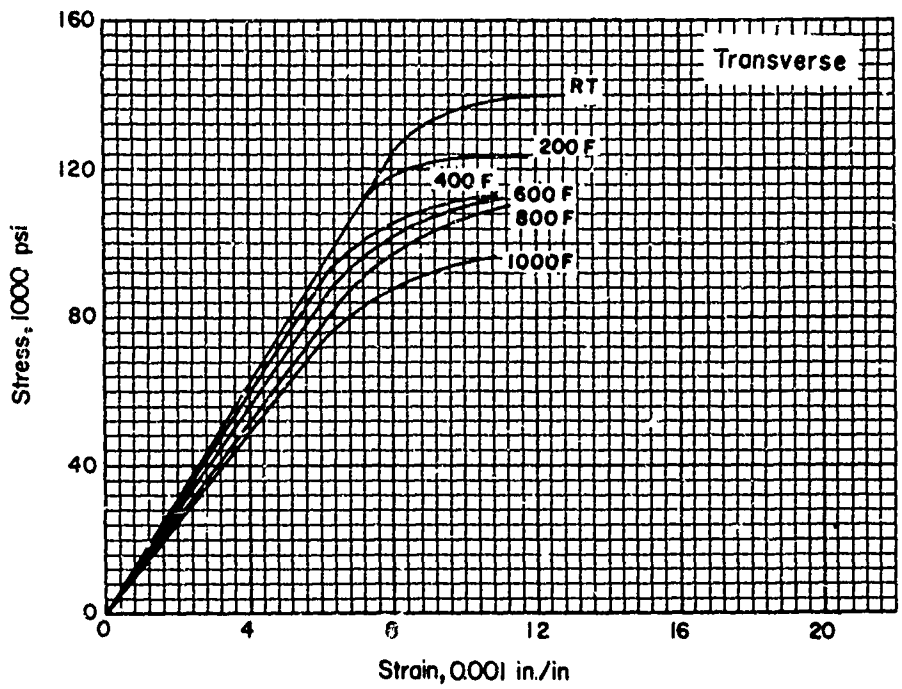

FIGURE 5-6.2.3-4. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

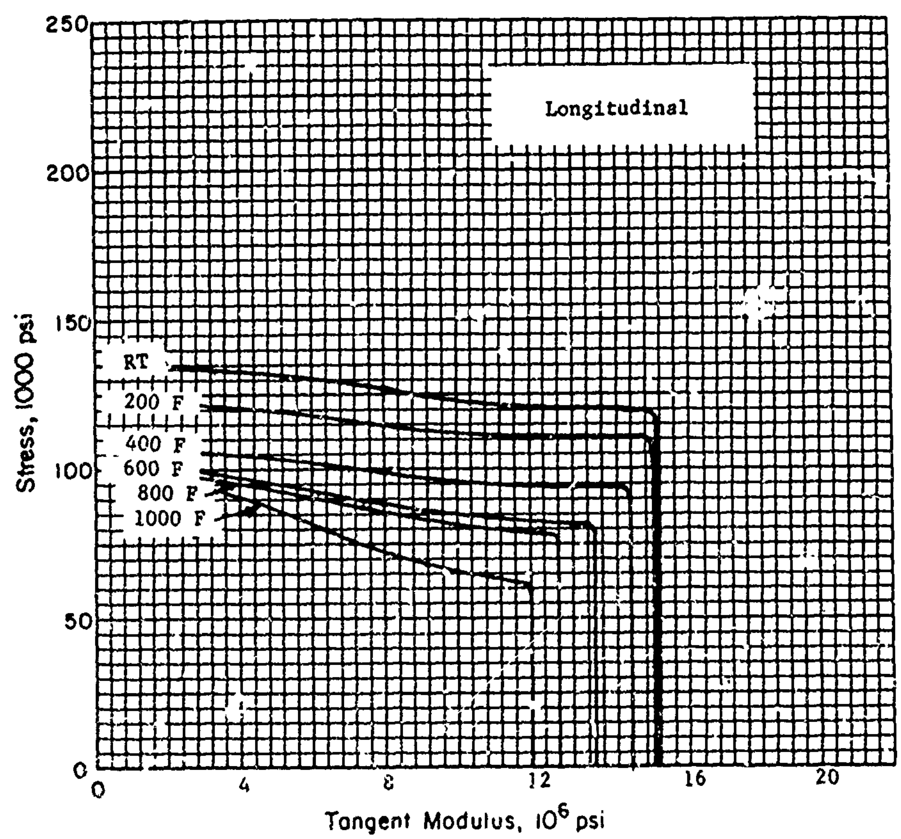

FIGURE 5-6.2.3-5. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR ANNEALED Ti-13V-1.Cr-3Al ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

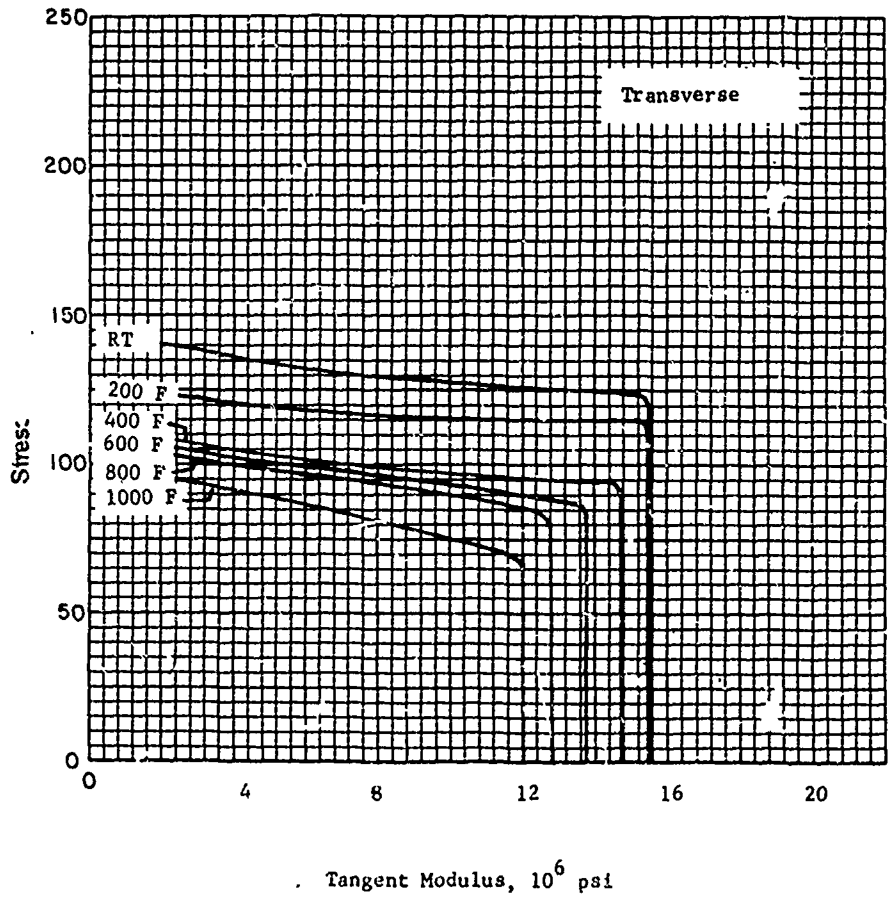

FIGURE 5-6.2.3-6. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR ANNEALED Ti-13V-11Cr-3Al ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

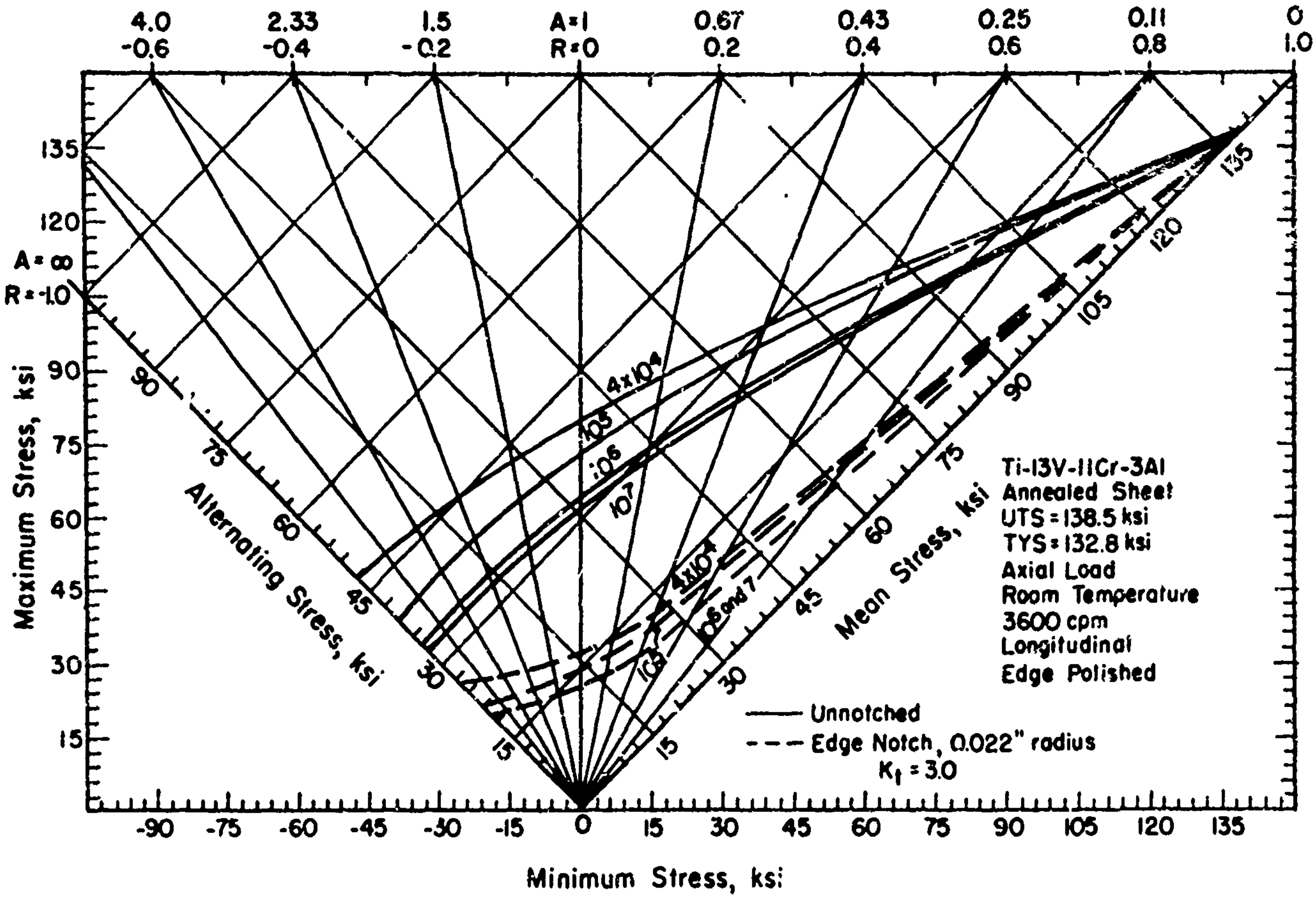

FIGURE 5-6.2.5-1. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR ANNEALED Ti-13V-11Cr-3Al ALLOY (SHEET) AT ROOM TEMPERATURE(47)

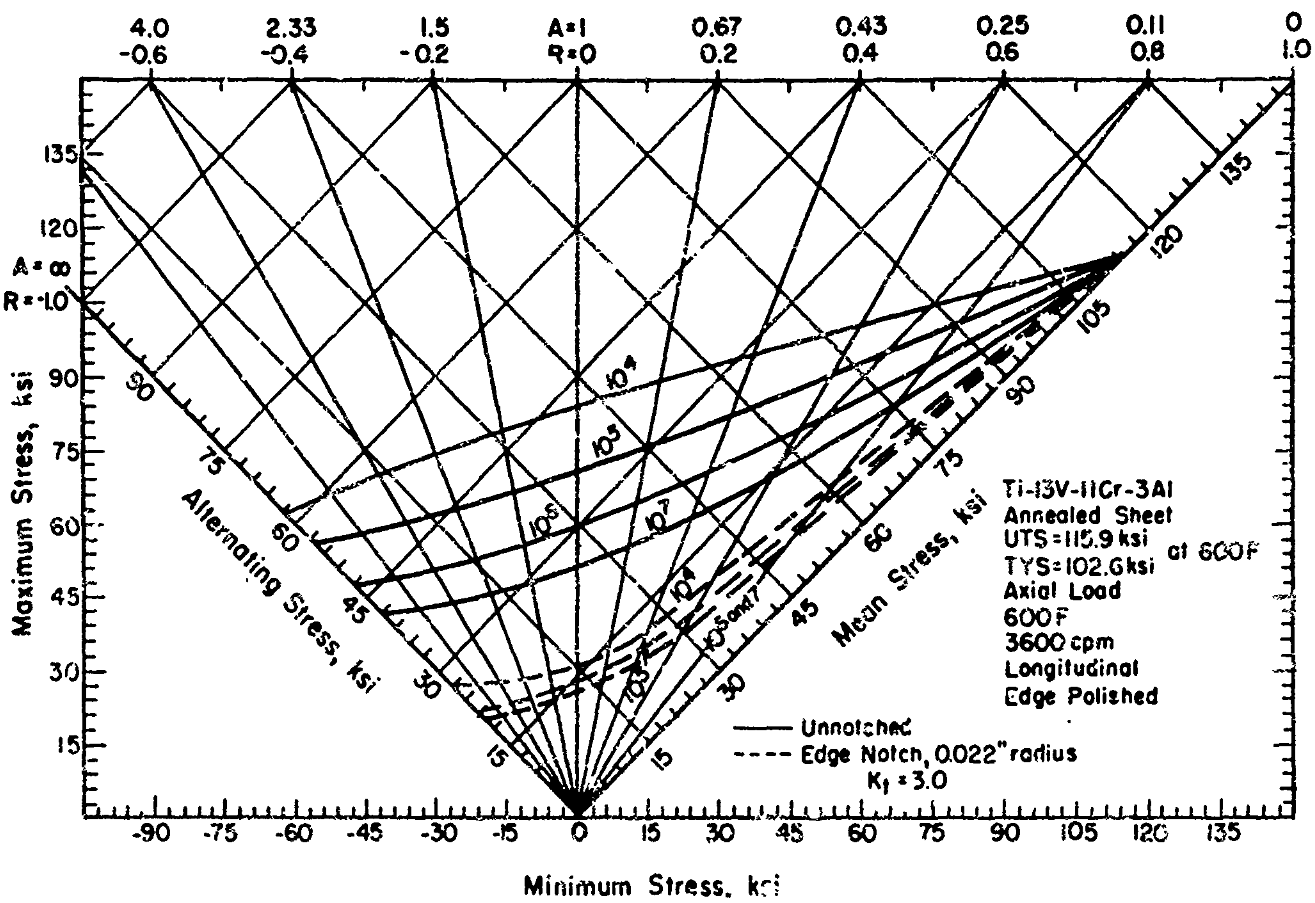

FIGURE 5-6.2.5-2. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR ANNEALED Ti-13V-11Cr-3Al ALLOY (SHEET) AT 600 F[47]

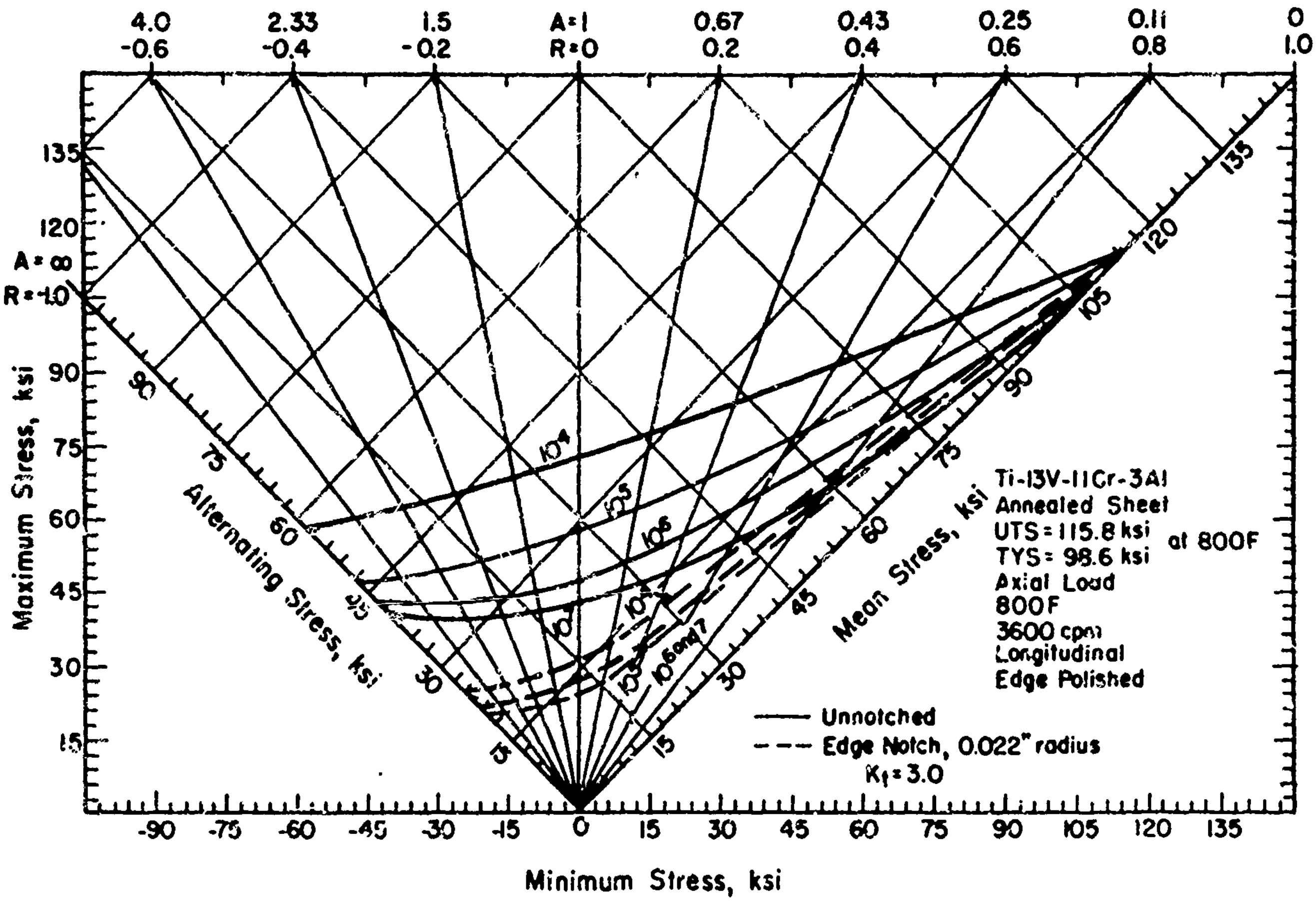

FIGURE 5-6.2.5-3. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR ANNEALED Ti-13V-11Cr-3Al ALLOY (SHEET) AT 800 F[(47)]

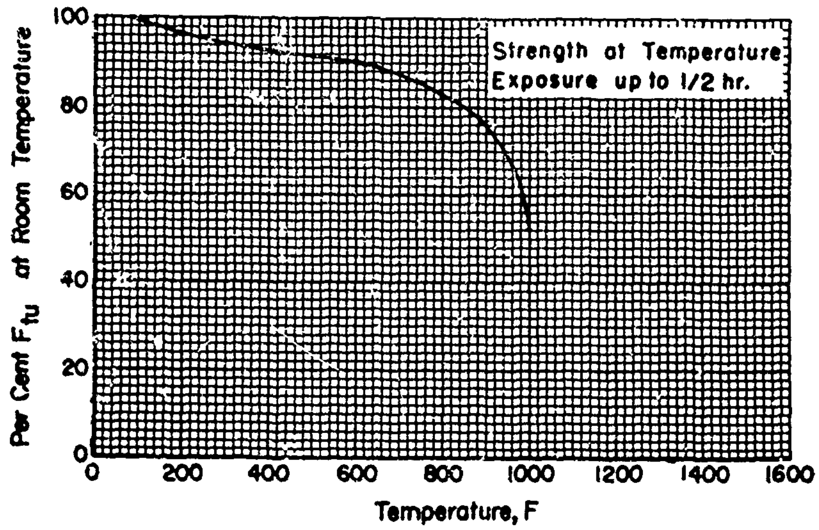

FIGURE 5-6.3.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET

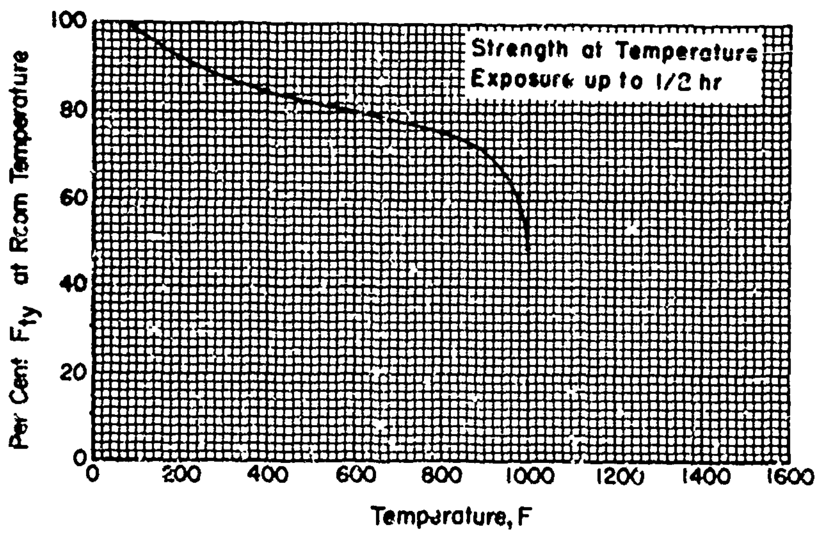

FIGURE 5-6.3.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET

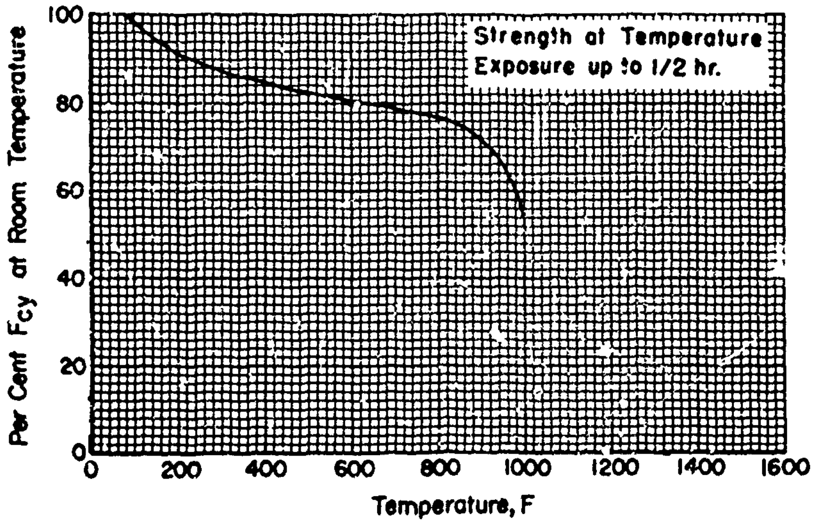

FIGURE 5-6.3.1-3. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET

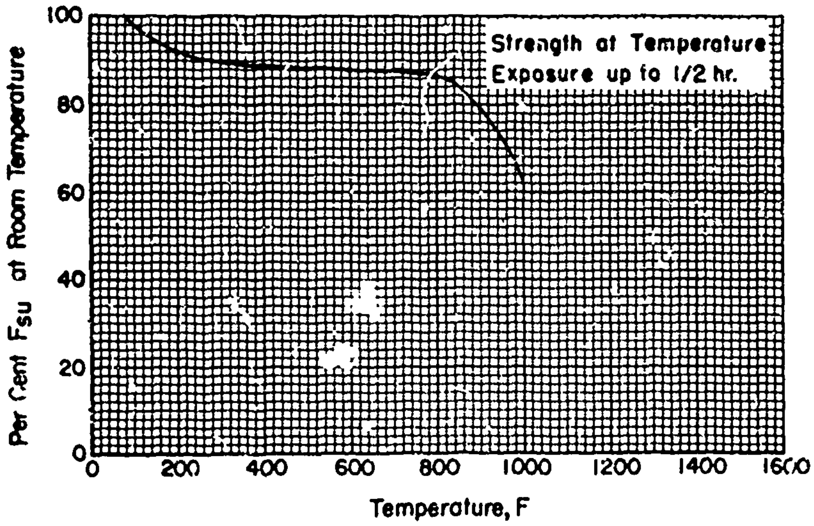

FIGURE 5-6.3.1-4. EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET

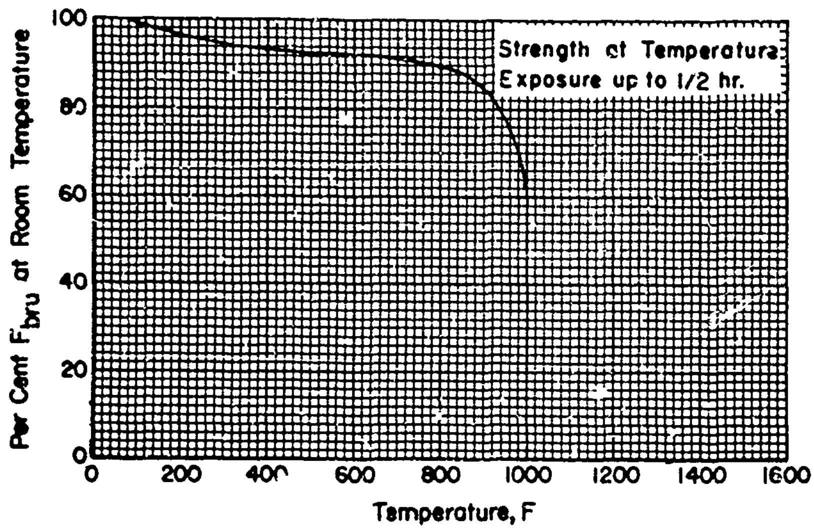

FIGURE 5-6.3.1-5. EFFECT OF TEMPERATURE ON THE ULTIMATE BEARING STRENGTH (F_{bru}) OF SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET

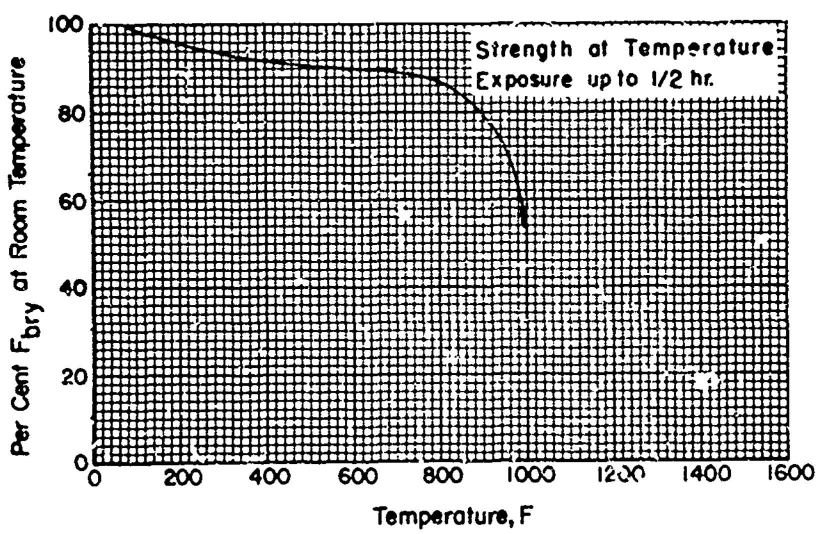

FIGURE 5-6.3.1-6. EFFECT OF TEMPERATURE ON THE BEARING YIELD STRENGTH (F_{bry}) OF SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET

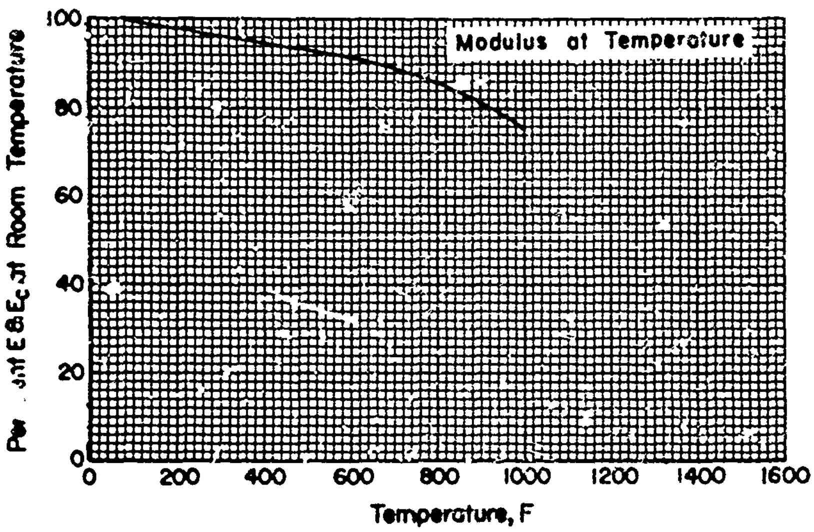

FIGURE 5-6.3.1-7. EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E AND E_c) OF SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET

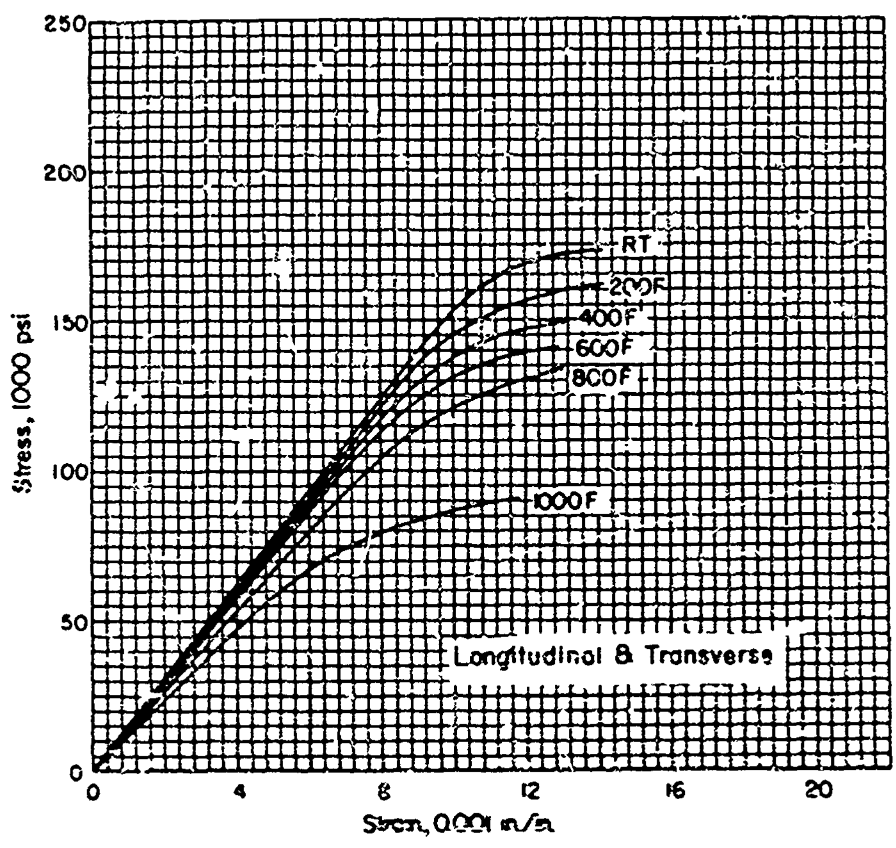

FIGURE 5-6.3.3-1 TYPICAL TENSILE STRESS-STRAIN CURVES FOR SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

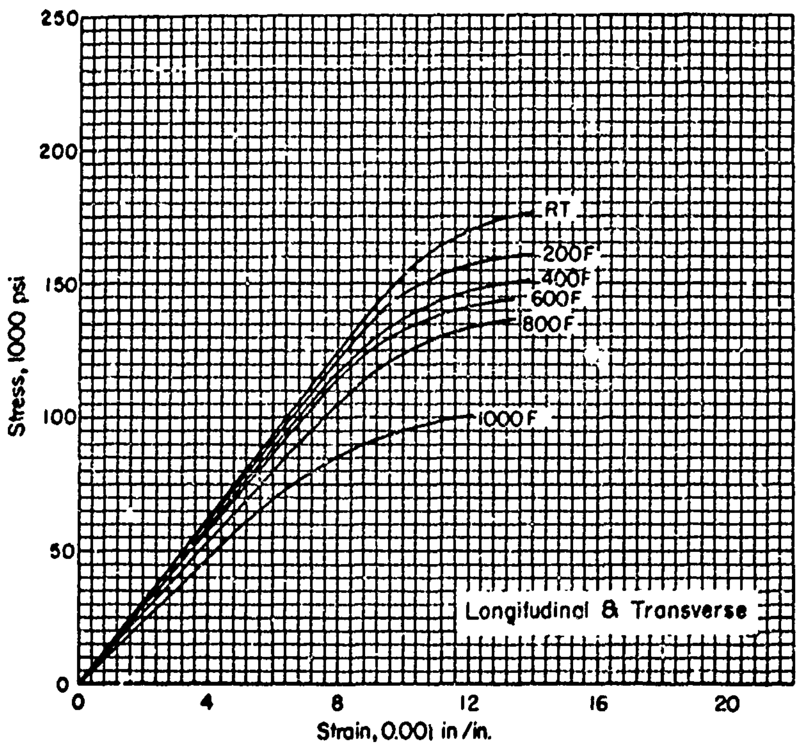

FIGURE 5-6.3.3-2. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

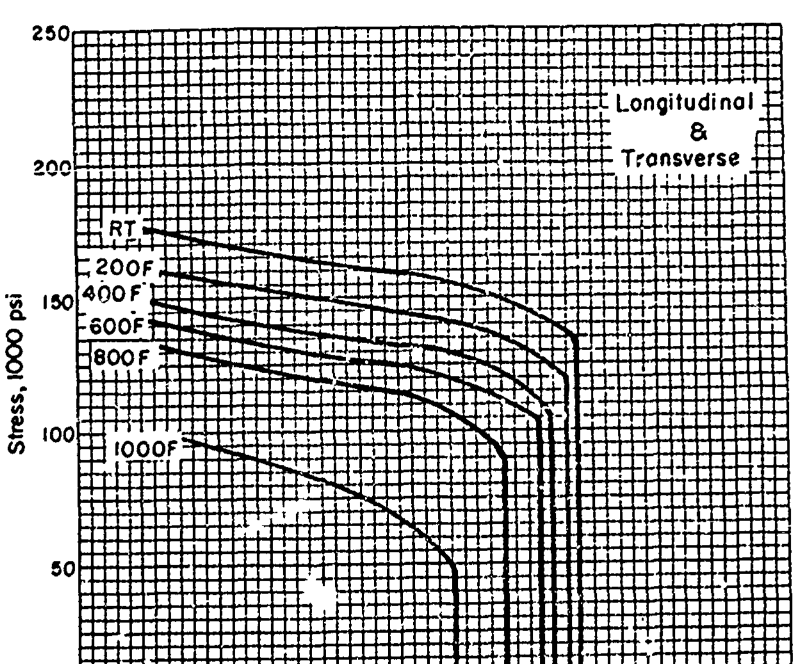

FIGURE 5-6.3.3-3. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

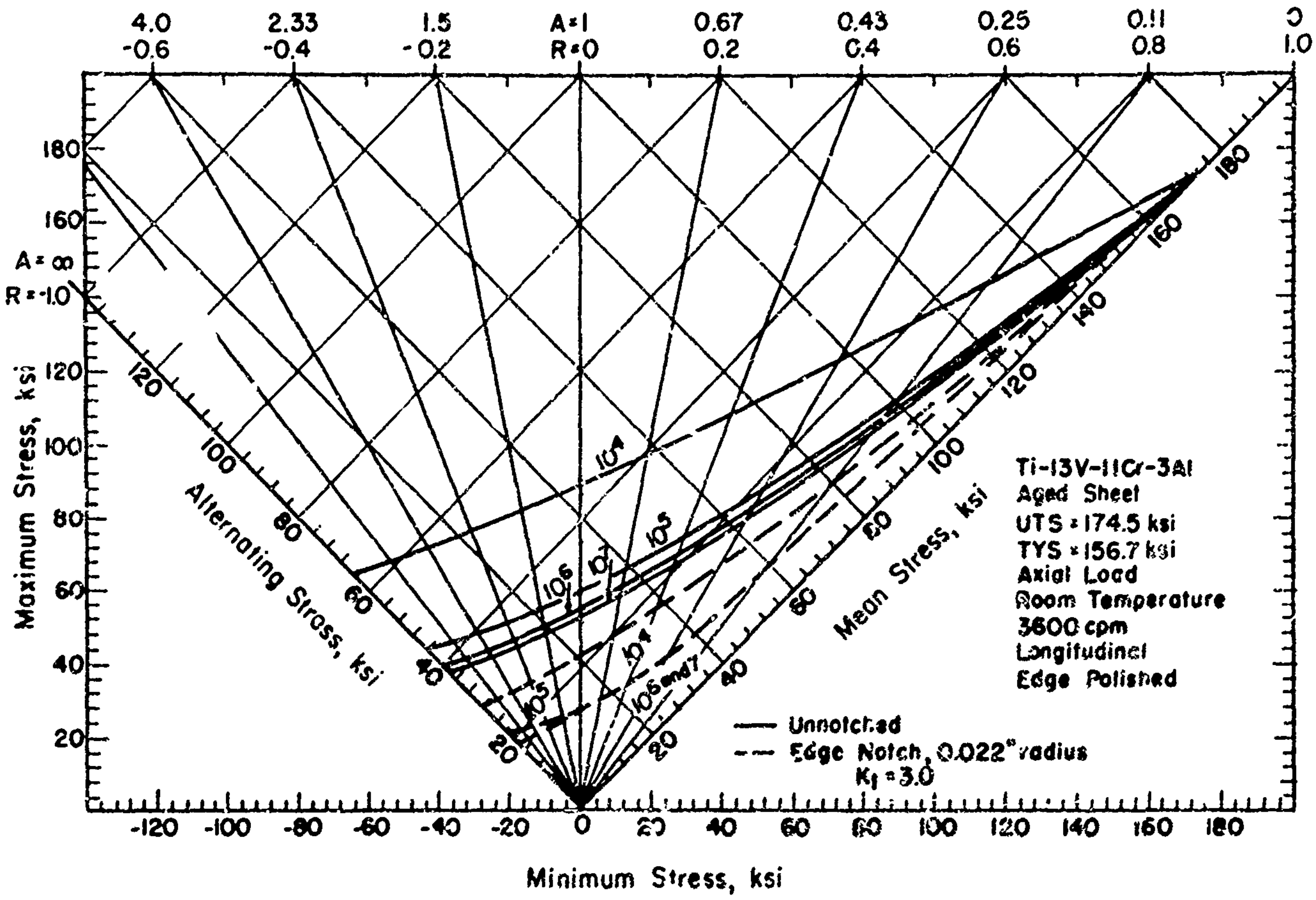

FIGURE 5-6.3.5-1. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY (SHEET) AT ROOM TEMPERATURE(47)

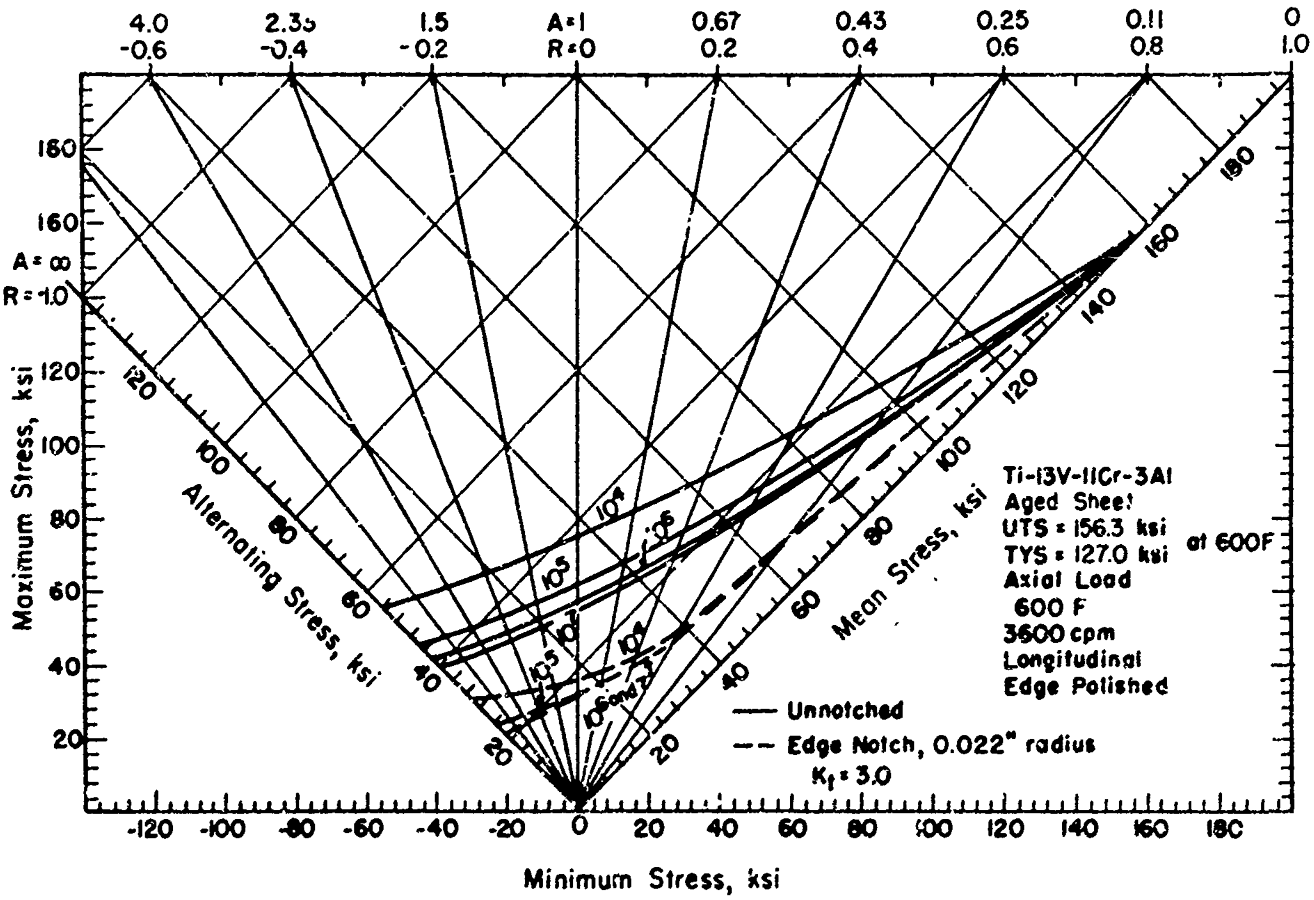

FIGURE 5-6.3.5-2. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY (SHEET) AT 600 F(47)

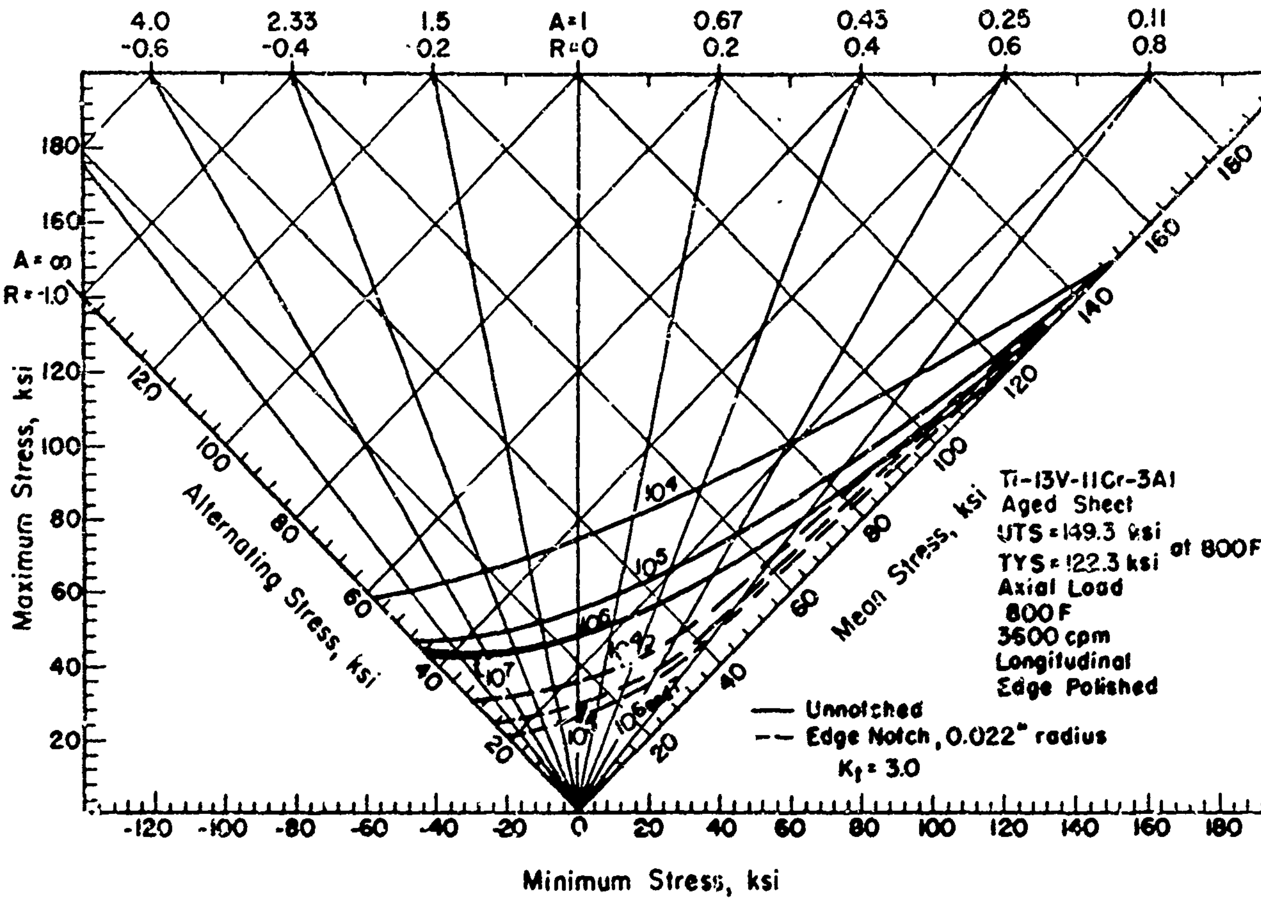

FIGURE 5-6.3.5-3. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR SOLUTION-TREATED AND AGED Ti-13V-11Cr-3Al ALLOY (SHEET) AT 800 F(47)

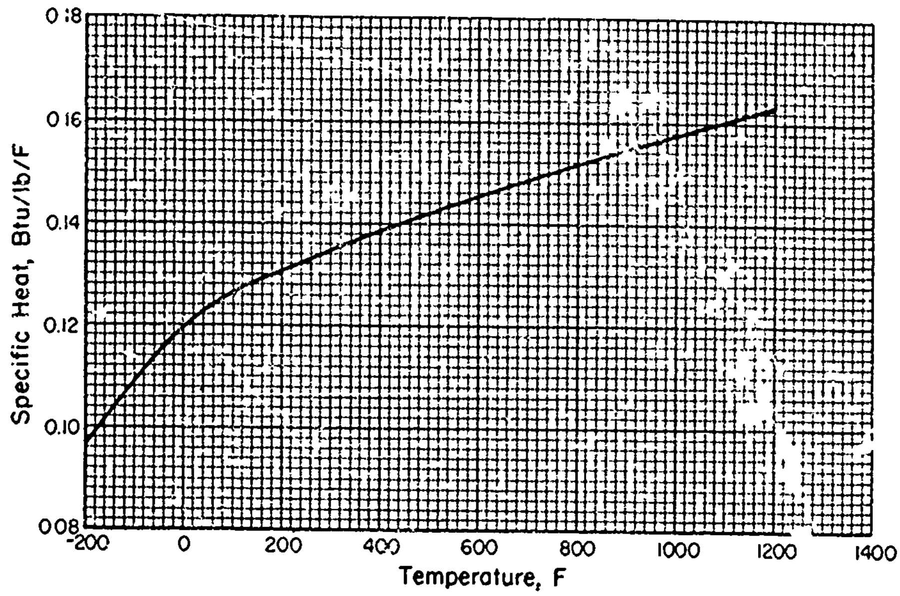

FIGURE 5-6.4-1. EFFECT OF TEMPERATURE ON THE SPECIFIC HEA (C) OF Ti-13V-11Cr-3Al(19)

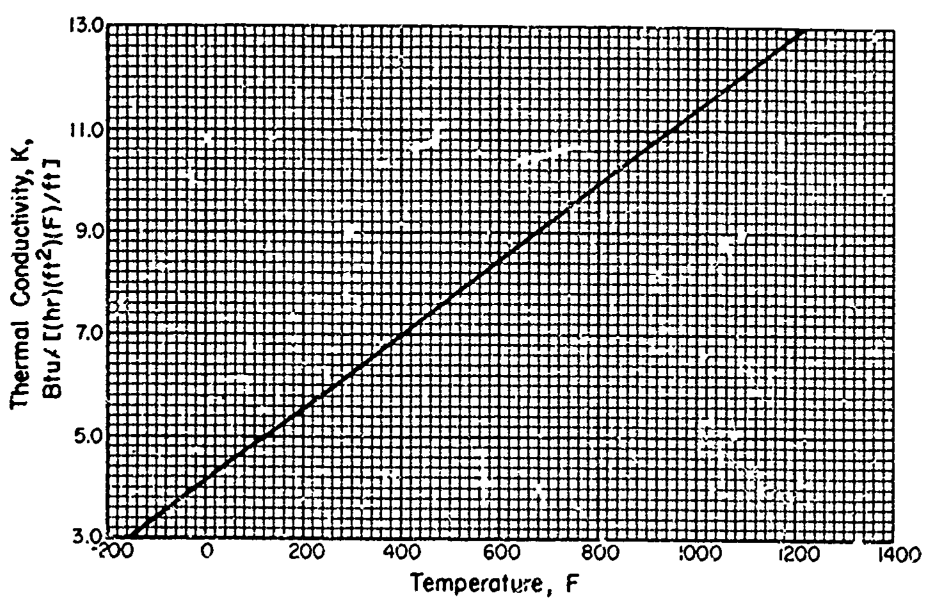

FIGURE 5-6.4-2. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY (K) OF Ti-13V-11Cr-3Al(19)

Note: These figures differ from corresponding curves in MIL-HDBK-5

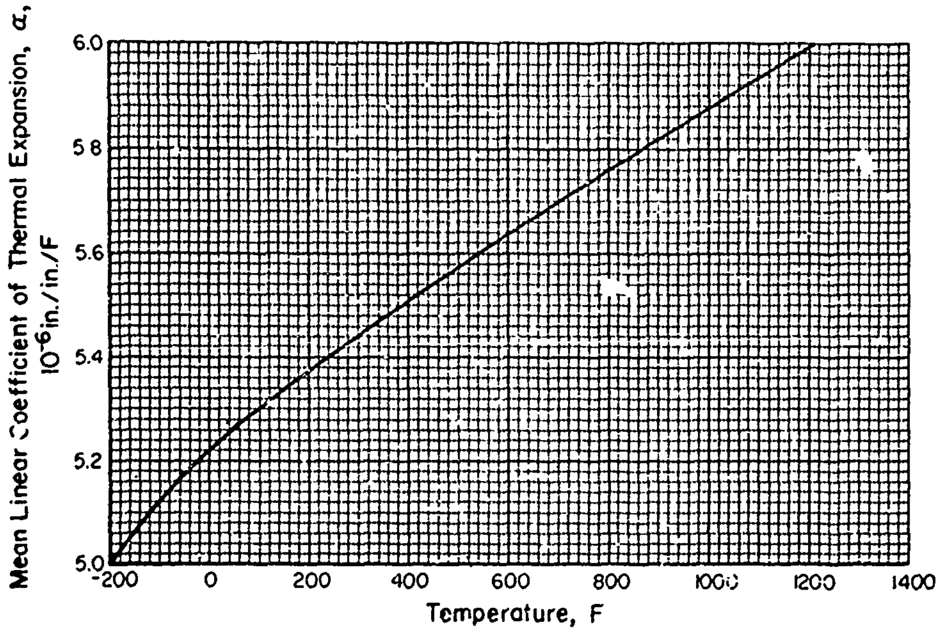

FIGURE 5-6.4-3. MEAN LINEAR COEFFICIENT OF THERMAL EXPANSION (α) OF Ti-13V-11Cr-3Al BETWEEN ROOM TEMPERATURE AND INDICATED TEMPERATURE[19]

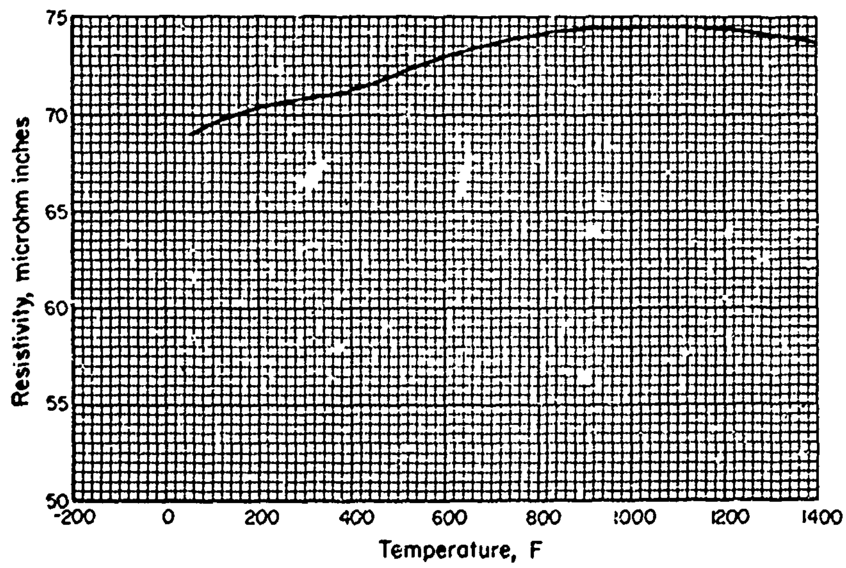

FIGURE 5-6.4-4. EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY (ρ) OF Ti-13V-11Cr-3Al[9]

5-7 Titanium Alloy Ti-4Al-3Mo-1V

5-7.0 SPECIFICATIONS AND FORMS

This section covers titanium alloy Ti-4Al-3Mo-1V of the following specifications and forms:

Specification	Form
MIL-T-9046	Sheet, strip, and plate
MIL-H-81200	Heat treatment, all forms

5-7.1 ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES

Table 5-7.1-1 summarizes the design mechanical properties of titanium alloy Ti-4Al-3Mo-1V sheet, strip, and plate at room temperature.

5-7.3 ENVIRONMENTAL EFFECTS FOR SOLUTION-TREATED AND AGED MATERIAL

5-7.3.1 Elevated Temperature Effects

The effect of temperature data are presented in Figures 5-7.3.1-1 through 5-7.3.1-6.

5-7.3.3 Stress-Strain and Tangent Modulus Curves

Typical compressive and tensile stress-strain curves for room and elevated temperatures are presented in Figures 5-7.3.3-1 and 5-7.3.3-2. The effect of temperature on the tensile and compressive modulus of elasticity is shown in Figure 5-7.3.3-3. Figure 5-7.3.3-4 presents typical compressive tangent modulus curves at room and elevated temperature.

5-7.3.5 Fatigue Effects

Typical constant-life fatigue diagrams at room and elevated temperatures for unnotched and notched Ti-4Al-3Mo-1V are shown in Figures 5-7.3.5-1 to 5-7.3.5-6.

5-7.4 THERMOPHYSICAL EFFECTS

The effect of temperature on physical properties is shown in Figures 5-7.4-1 to 5-7.4-3.

TABLE 5-7.1-1. ROOM TEMPERATURE DESIGN MECHANICAL PROPERTIES OF Ti-4Al-3Mo-1V

Alloy	MIL-T-9046 Type III Composition B								
Form	Sheet and strip			Plate					
Condition	Annealed	Solution-treated and aged							
Thickness or diameter, in.	--	$\leq$0.187[a]		0.188 to 0.250	0.251 to 0.500	0.501 to 0.750	0.751 to 1.000	1.001 to 1.500	1.501 to 4.000
Basis	S	A	B	S	S	S	S	S	S
Mechanical properties:									
F_{tu}, ksi	[redacted]								
F_{ty}, ksi									
F_{cy}, ksi									
F_{su}, ksi									
F_{bru}, ksi:									
(e/D = 1.5)									
(e/D = 2.0)									
F_{bry}, ksi:									
(e/D = 1.5)									
(e/D = 2.0)									
e, per cent:									
In 2 in.									
E, 10^6 psi	15.5								
E_c, 10^6 psi	16.0								
G, 10^6 psi	6.0								
μ	0.32								
η	-								
ω	0.162								

Values in parentheses () are tentative values.

[a] Thickness 0.025 inch and above. [b] 5 - 0.050 in. and above; 4 - 0.033 to 0.049 in; 3 - 0.032 in. and below.

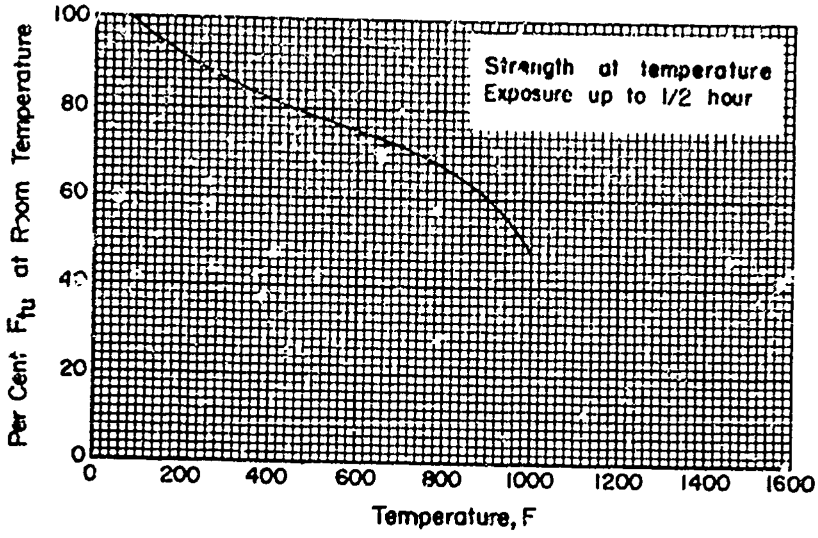

FIGURE 5-7.3.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY

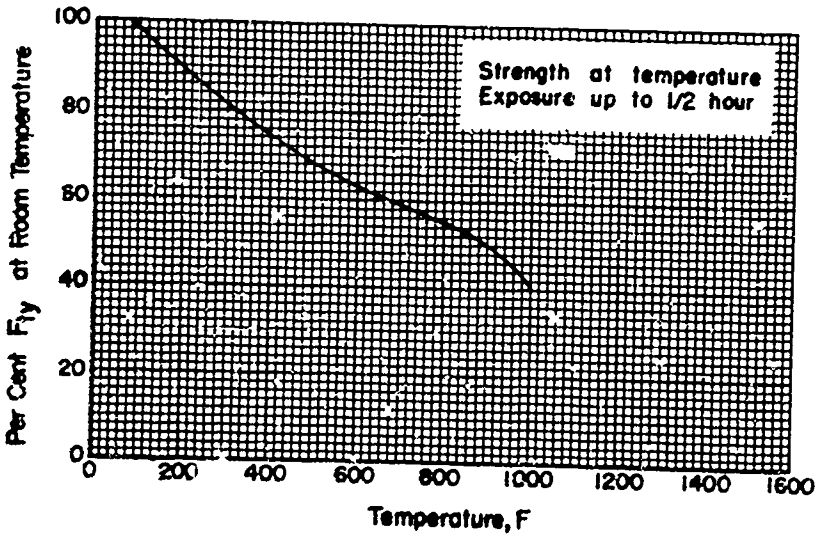

FIGURE 5-7.3.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY

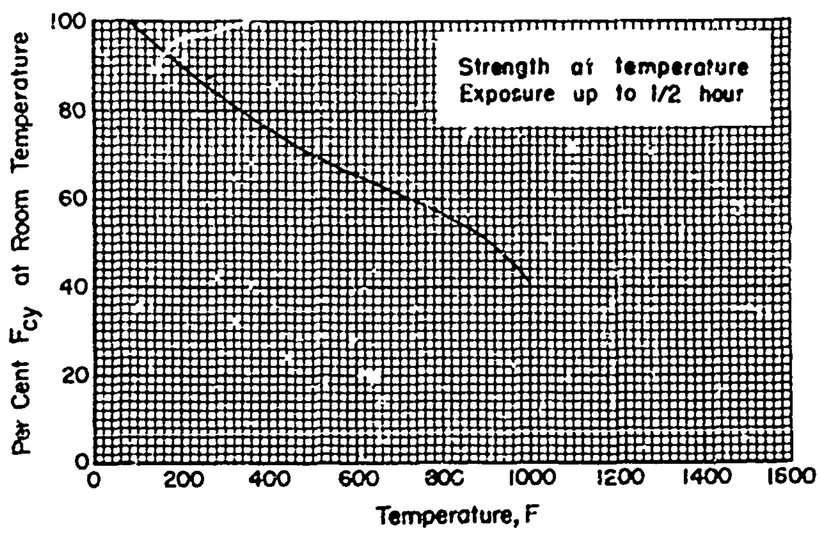

FIGURE 5-7.3.1-3. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF SOLUTION-TREATED AND AGED i-4Al-3Mo-1V ALLOY

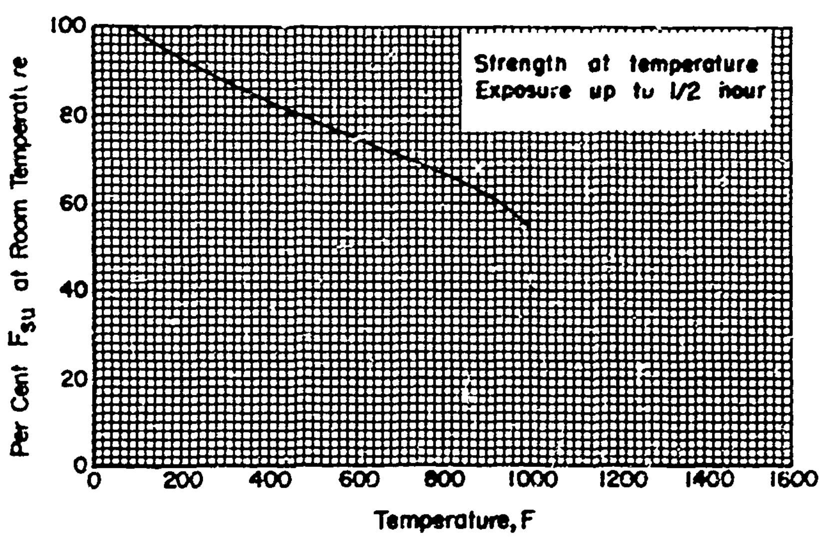

FIGURE 5-7.3.1-4. EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY

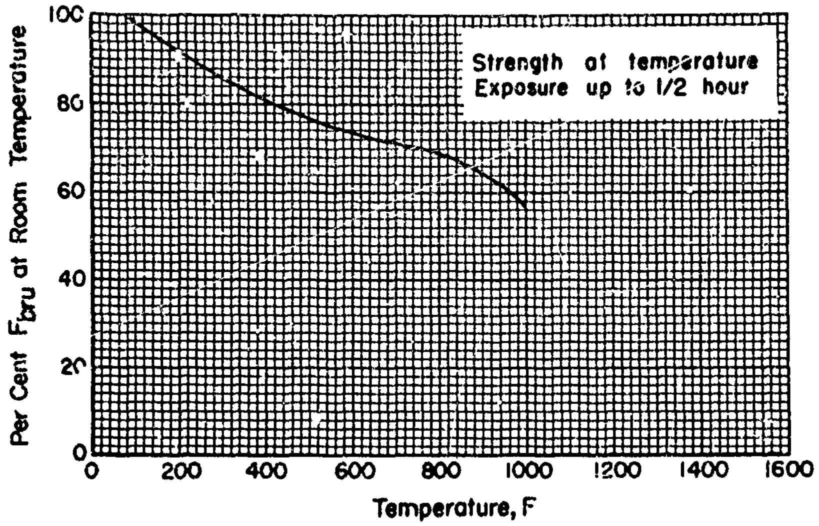

FIGURE 5-7.3.1-5. EFFECT OF TEMPERATURE ON THE ULTIMATE BEARING STRENGTH (F_{bru}) OF SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY

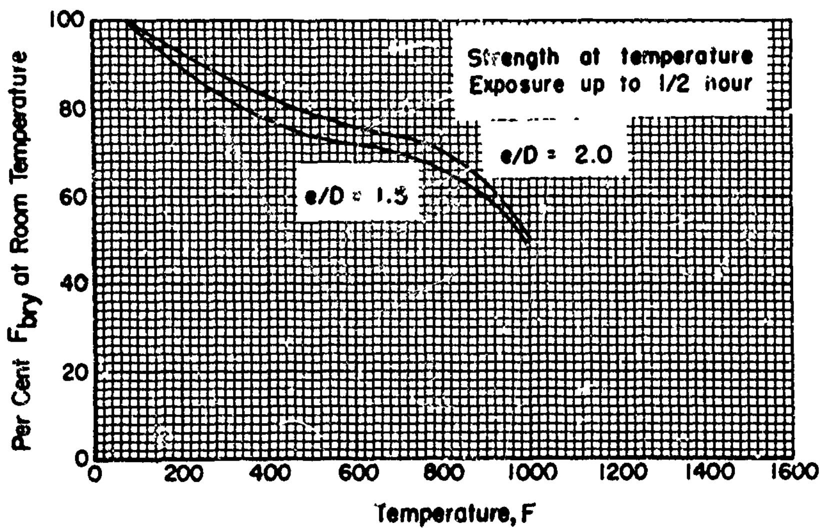

FIGURE 5-7.3.1-6. EFFECT OF TEMPERATURE ON THE BEARING YIELD STRENGTH (F_{bry}) OF SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY

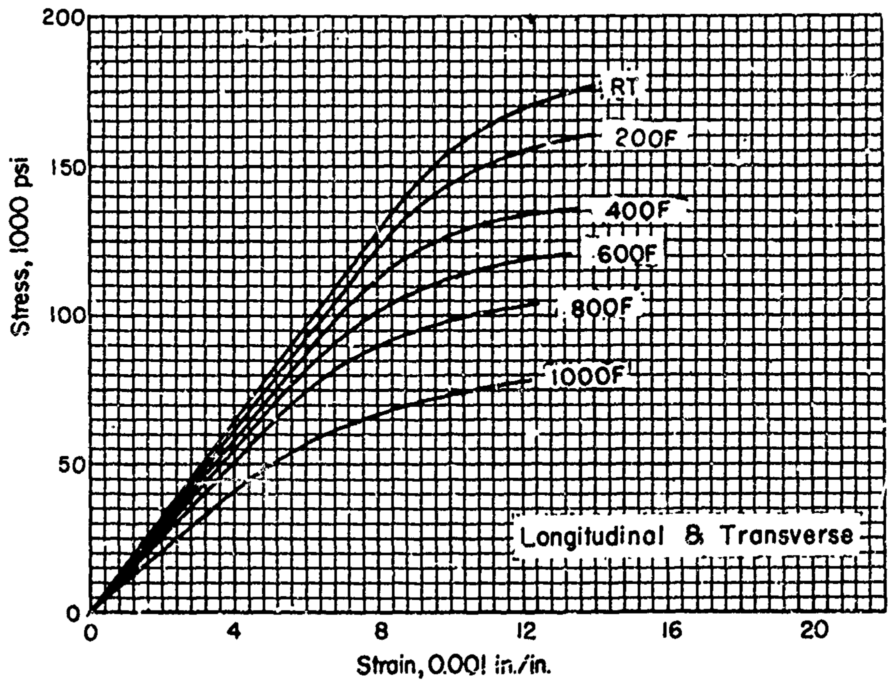

FIGURE 5-7.3.3-1. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

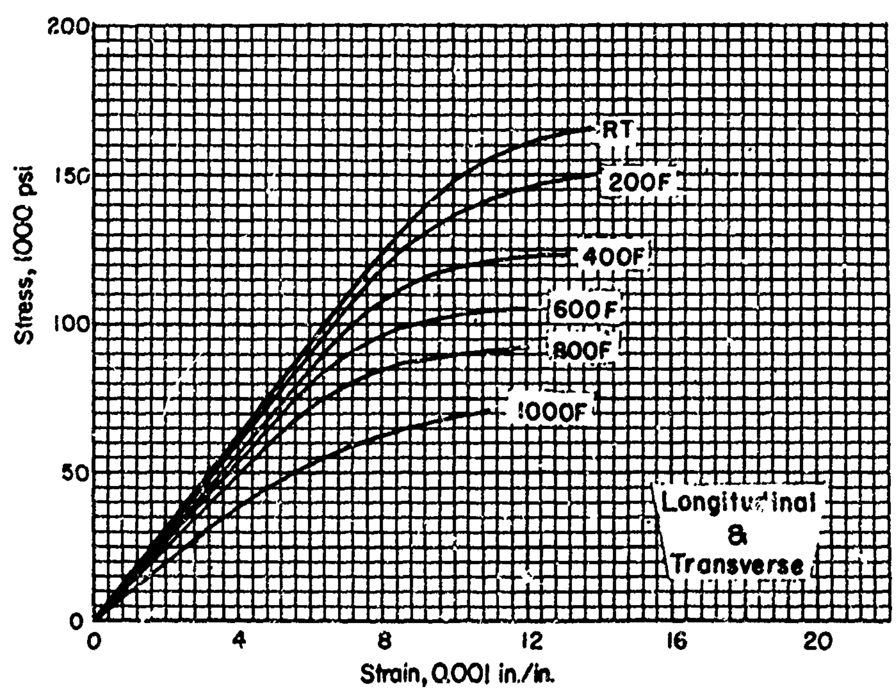

FIGURE 5-7.3.3-2. TYPICAL TENSILE STRESS-STRAIN CURVES FOR SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

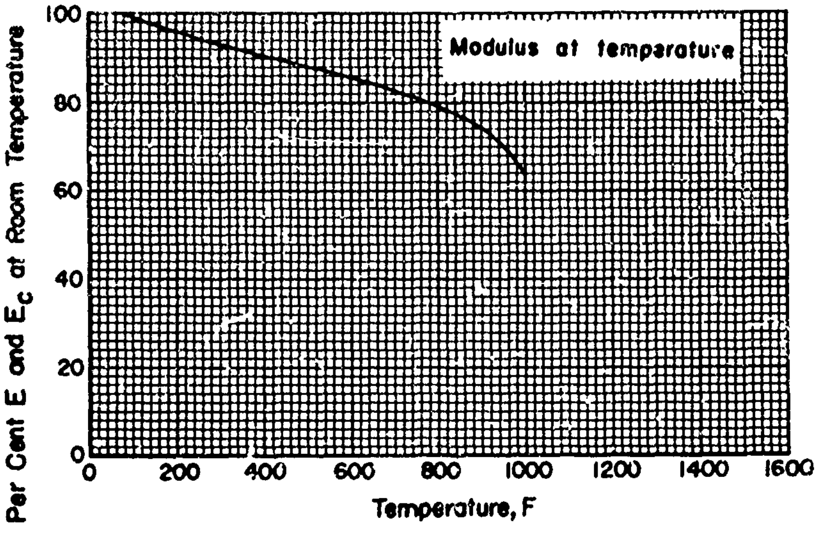

FIGURE 5-7.3.3-3. EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E AND E_c) OF SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY

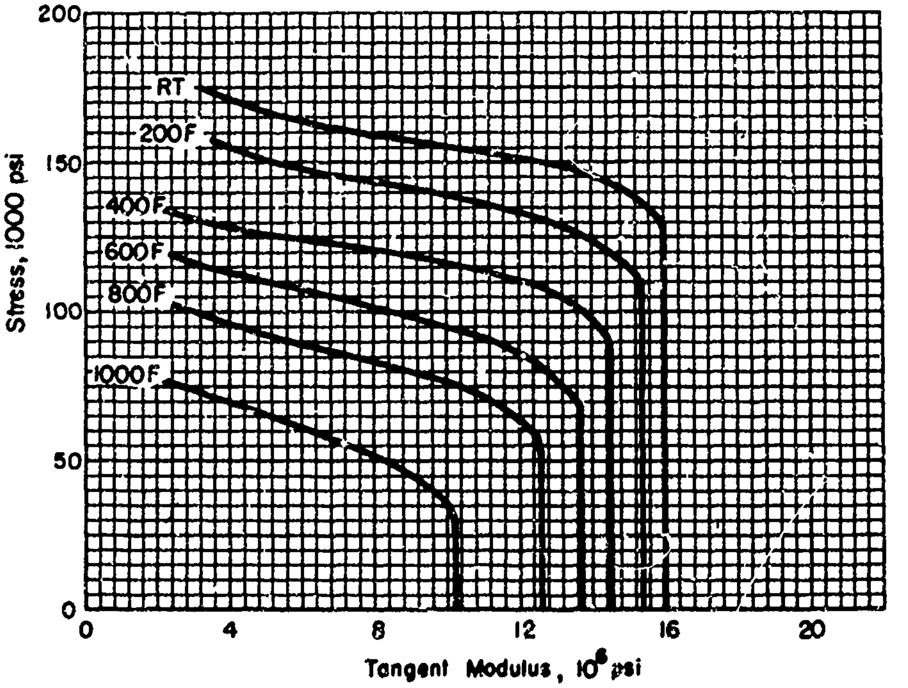

FIGURE 5-7.3.3-4. TYPICAL COMPRESSIVE TANGENT MODULUS CURVES FOR SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES.

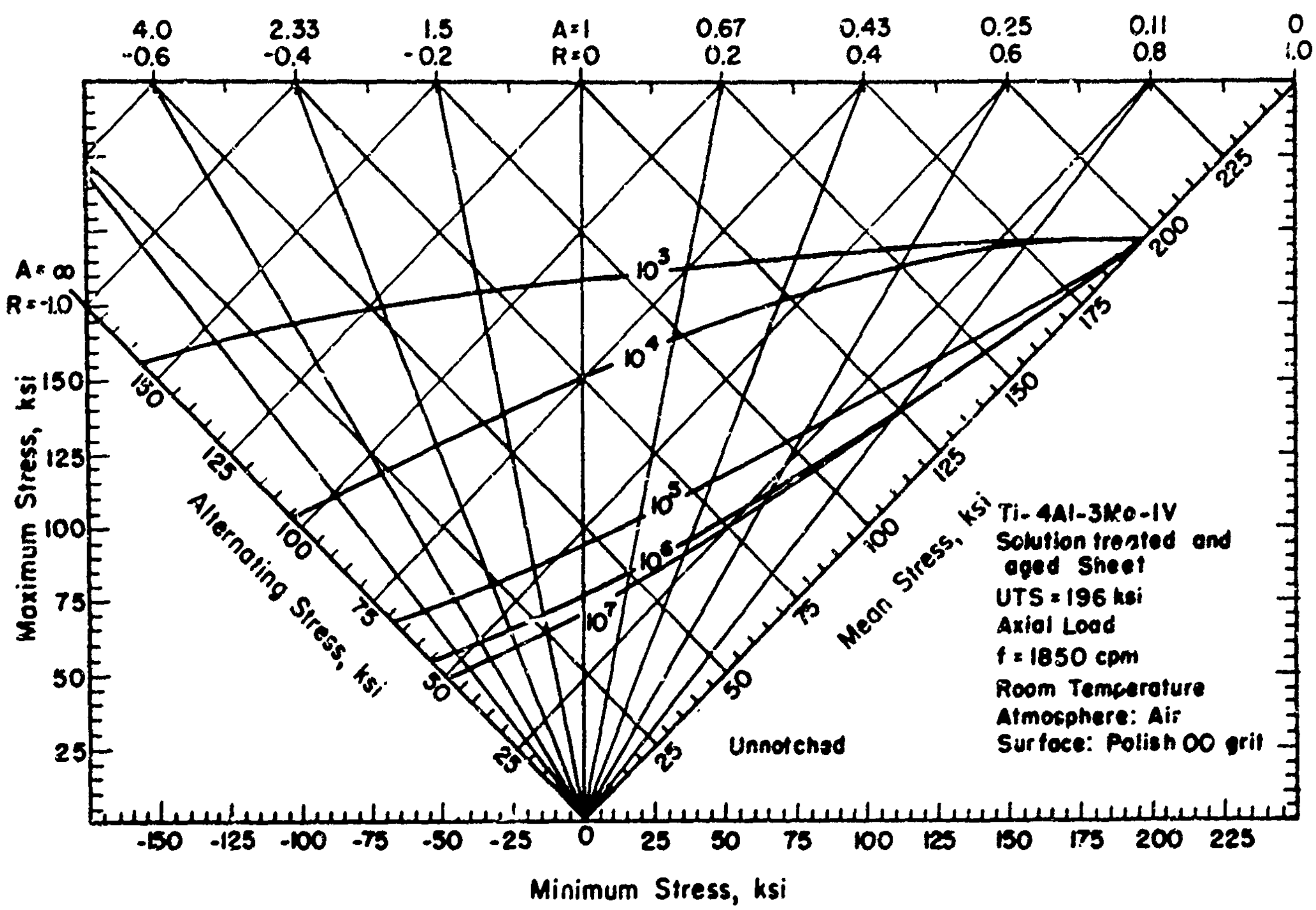

FIGURE 5-7.3.5-1. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR Ti-4Al-3Mo-1V (STA) AT ROOM TEMPERATURE

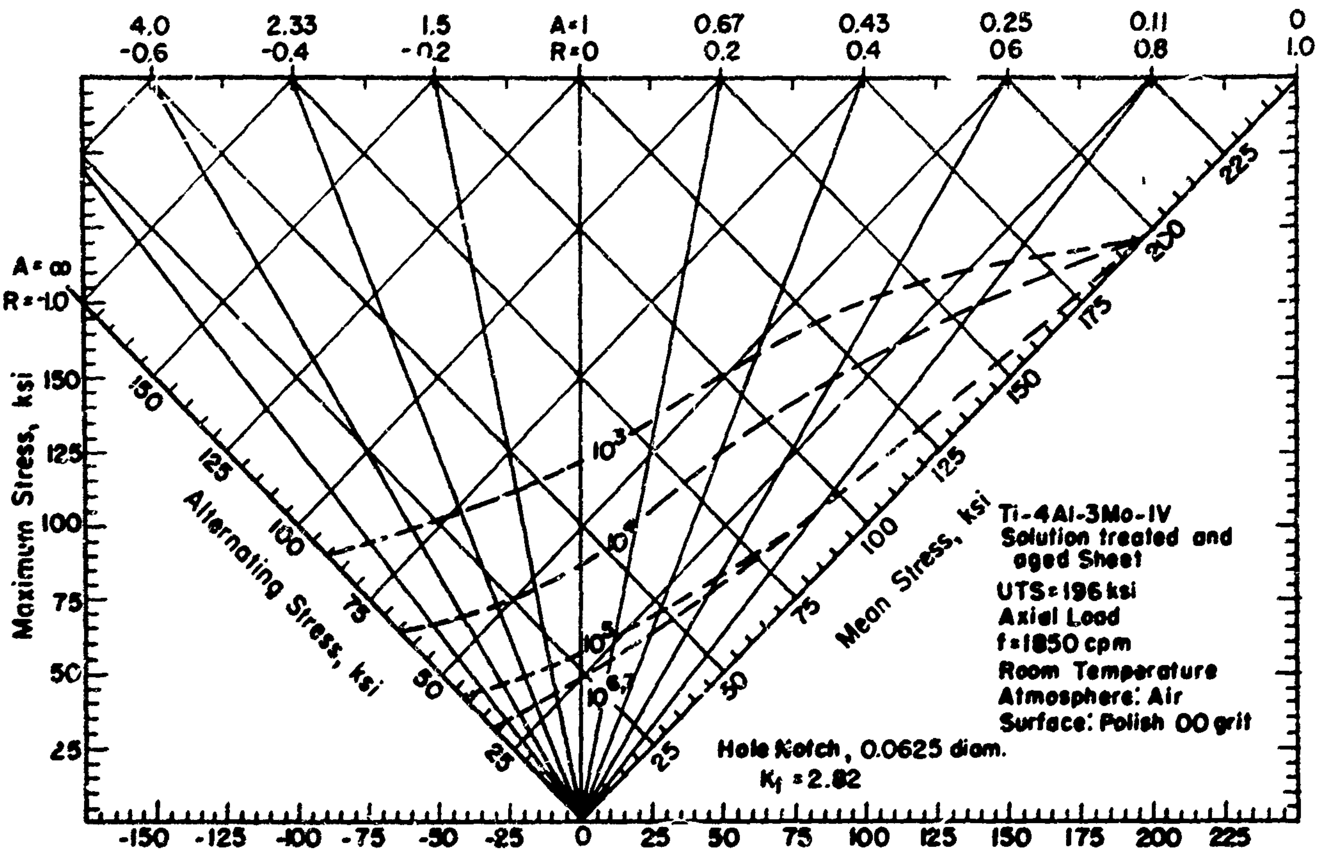

FIGURE 5-7.3.5-2. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR NOTCHED Ti-4Al-3Mo-1V (STA) AT ROOM TEMPERATURE

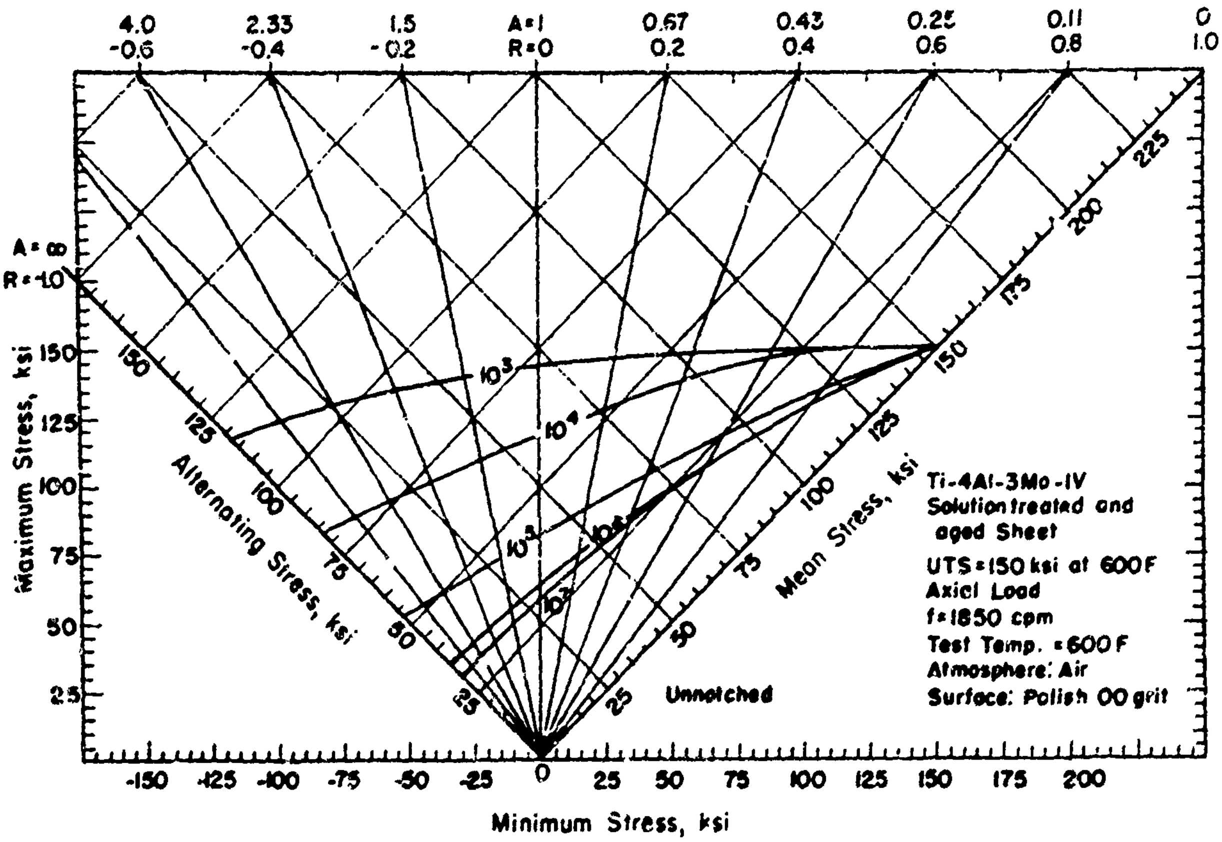

FIGURE 5-7.3.5-3. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR Ti-4Al-3Mo-1V (STA) AT 600 F

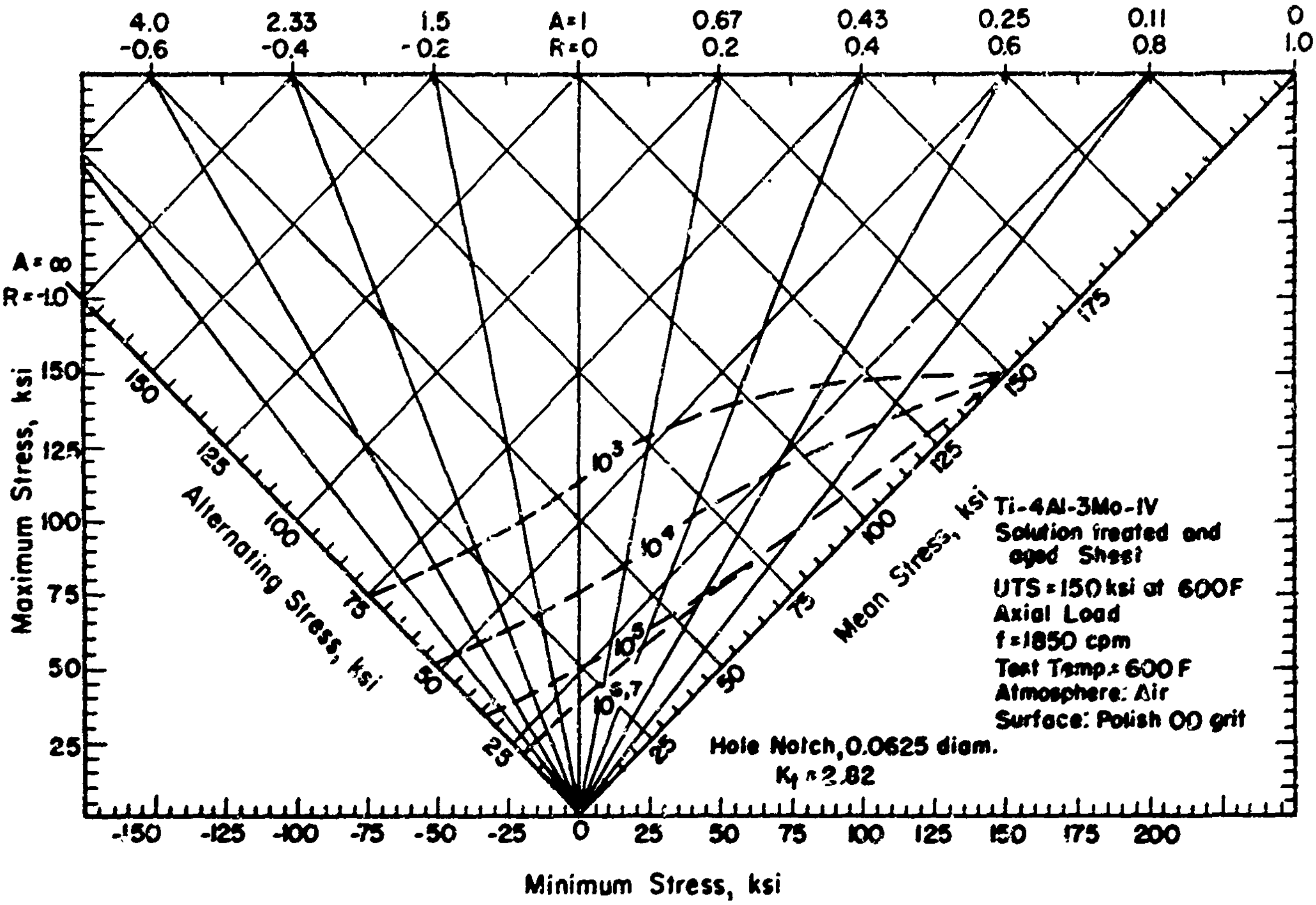

FIGURE 5-7.3.5-4. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR NOTCHED Ti-4A -3Mo-1V (STA) AT 600 F

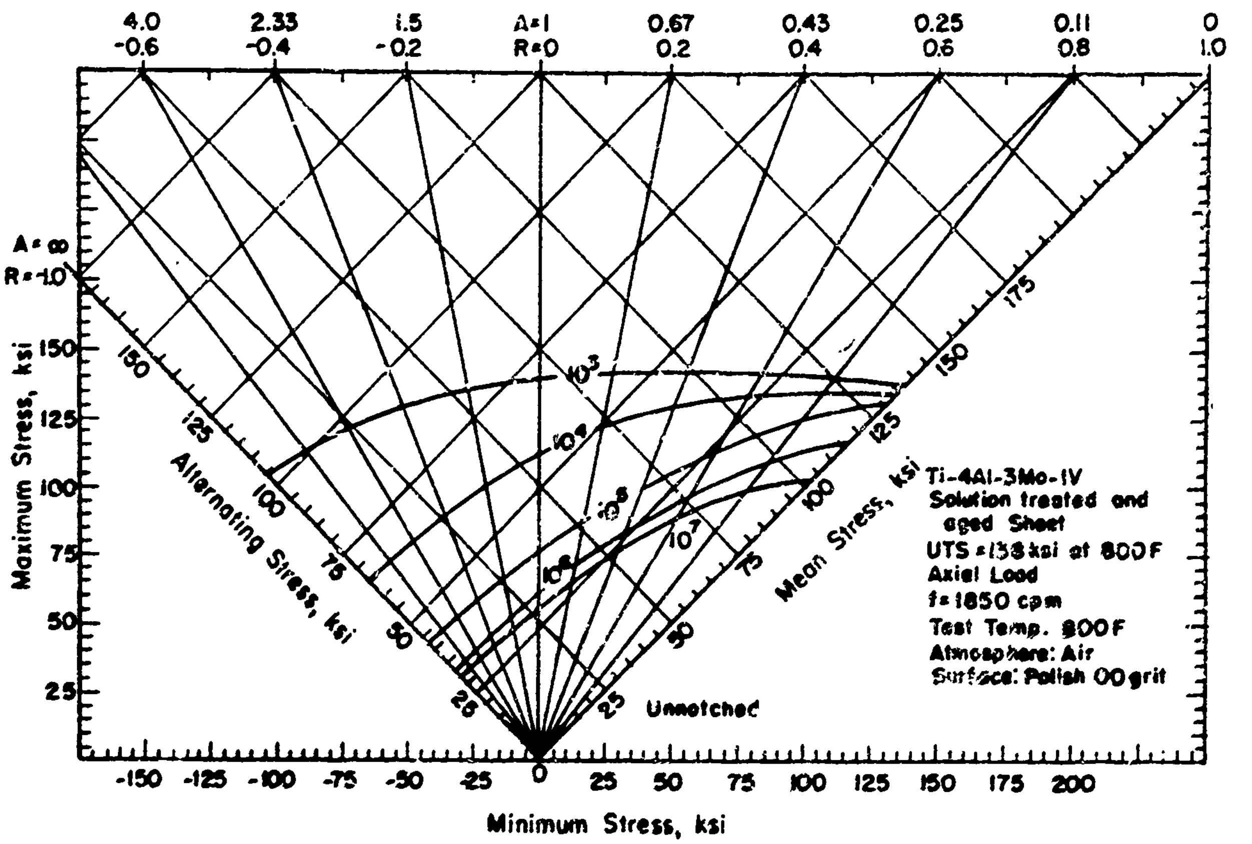

FIGURE 5-7.3.5-5. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR Ti-4Al-3Mo-1V (STA) AT 800 F

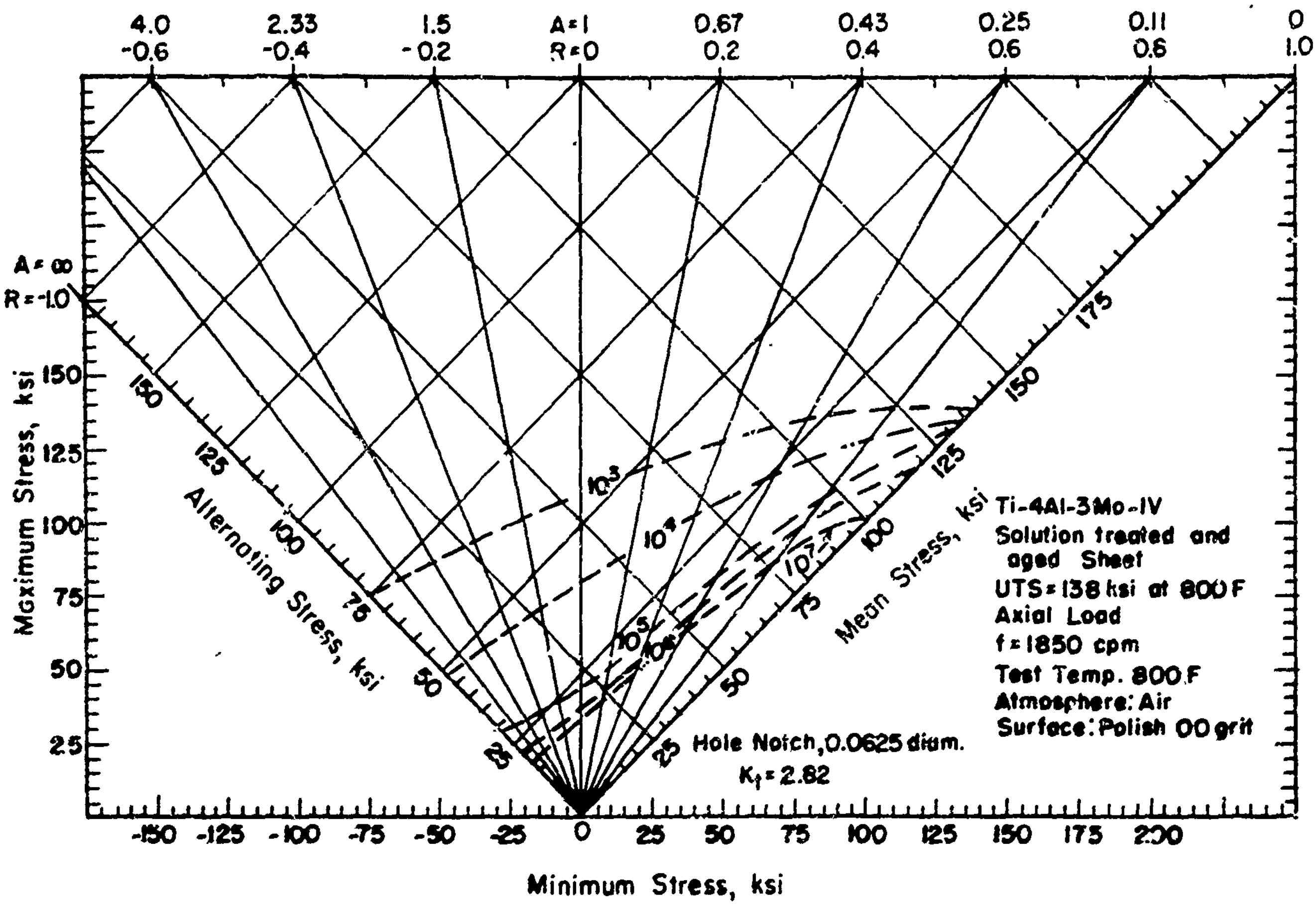

FIGURE 5-7.3.5-6. TYPICAL CONSTANT-LIFE FATIGUE DIAGRAM FOR NOTCHED Ti-4Al-3Mo-1V (STA) AT 800 F.

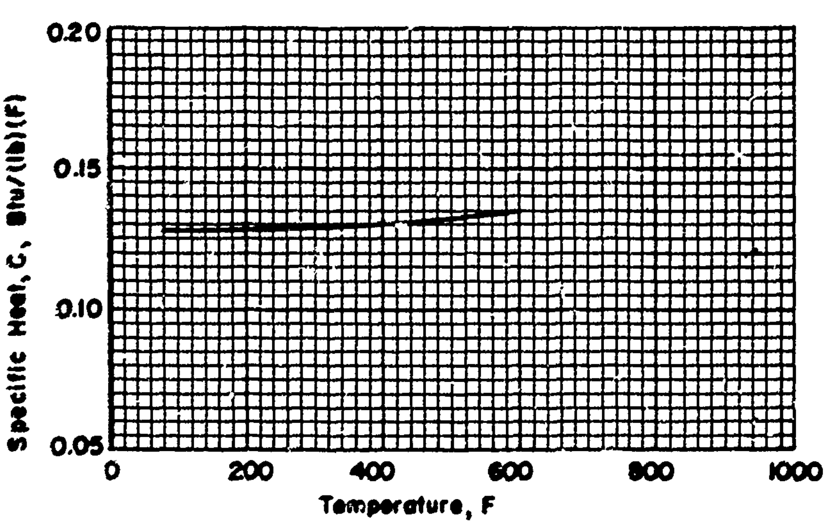

FIGURE 5-7.4-1. EFFECT OF TEMPERATURE ON THE SPECIFIC HEAT (C) OF Ti-4Al-3Mo-1V

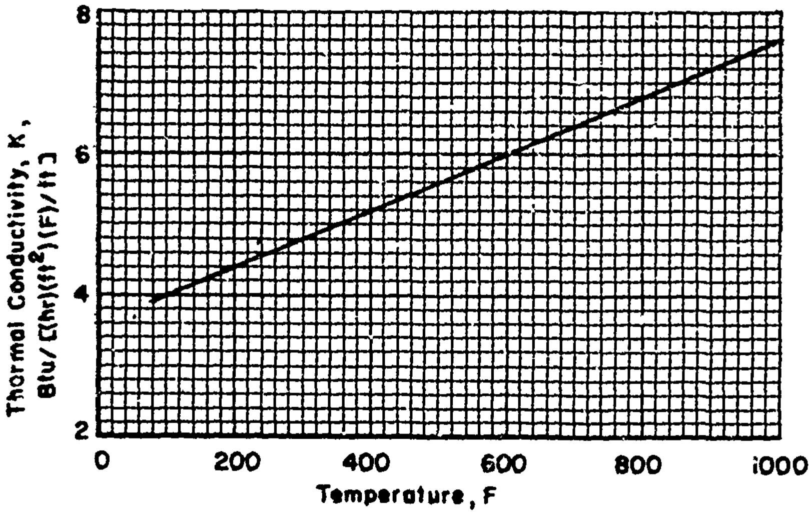

FIGURE 5-7.4-2. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY (K) OF Ti-4Al-3Mo-1V

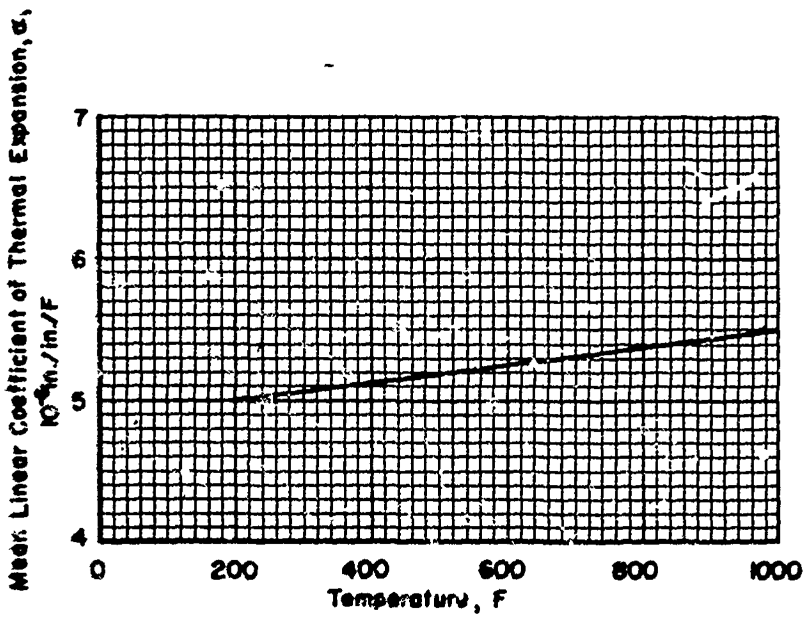

FIGURE 5-7.4-3. EFFECT OF TEMPERATURE ON THE MEAN COEFFICIENT OF THERMAL EXPANSION (α) OF Ti-4Al-3Mo-1V

5-8 Titanium Alloy Ti-679

5-8.0 SPECIFICATIONS AND FORMS

This section covers titanium alloy Ti-679 of the following specifications and forms:

Specification	Form
AMS DRAFT 49BH MIL-T-9047	Bars and forgings

5-8.1 ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES

Table 5-8.1-1 summarizes the design mechanical properties of titanium alloy Ti-679 at room temperature.

5-8.3 ENVIRONMENTAL EFFECTS FOR SOLUTION-TREATED AND AGED MATERIAL

5-8.3.1 Elevated-Temperature Effects

Effect of temperature data are presented in Figures 5-8.3.1-1 through 5-8.3.1-7.

5-8.3.3 Stress-Strain and Tangent Modulus Curves

5-8.3.4 Creep Effects

Creep properties of solution treated and aged Ti-679 are shown in Figure 5-8.3.4-1.

5-8.3.5 Fatigue Effects

Constant-life diagrams for fatigue behavior of extrusions at room and elevated temperatures are presented in Figures 5-8.3.5-1 through 5-8.3.5-3.

5-8.4 Thermophysical Effects

The effect of temperature on physical properties is displayed in Figures 5-8.4-2 through 5-8.4-4.

Note: This alloy is not included in MIL-HDBK-5.

[redacted]

Alloy	MIL-T-9047D Type III Composition G			
Form	Bars and forgings			
Condition	Annealed	Solution-treated and aged per MIL-H-81200		
Thickness or diameter, in.	≤ 3	≤ 1	$> 1, \leq 2$	$> 2, \leq 3$
Basis	S	S	S	S
Mechanical properties:				
F_{tu}, ksi	140	155	150	140
F_{ty}, ksi	130	145	140	130
F_{cy}, ksi	[redacted]	[redacted]	[redacted]	[redacted]
F_{su}, ksi	[redacted]	[redacted]	[redacted]	[redacted]
F_{bru}, ksi:				
(e/D = 1.5)	[redacted]	[redacted]	[redacted]	[redacted]
(e/D = 2.0)	[redacted]	[redacted]	[redacted]	[redacted]
F_{bry}, ksi:				
(e/D = 1.5)	[redacted]	[redacted]	[redacted]	[redacted]
(e/D = 2.0)	[redacted]	[redacted]	[redacted]	[redacted]
e, per cent:				
L	10	—	—	—
T	10	10	10	10
E, 10^6 psi	15.0			
E_c, 10^6 psi	15.5			
G, 10^6 psi	—			
μ	—			
n	—			
ω, lb/in.^{3}	0.174			

Values in parentheses () are tentative values

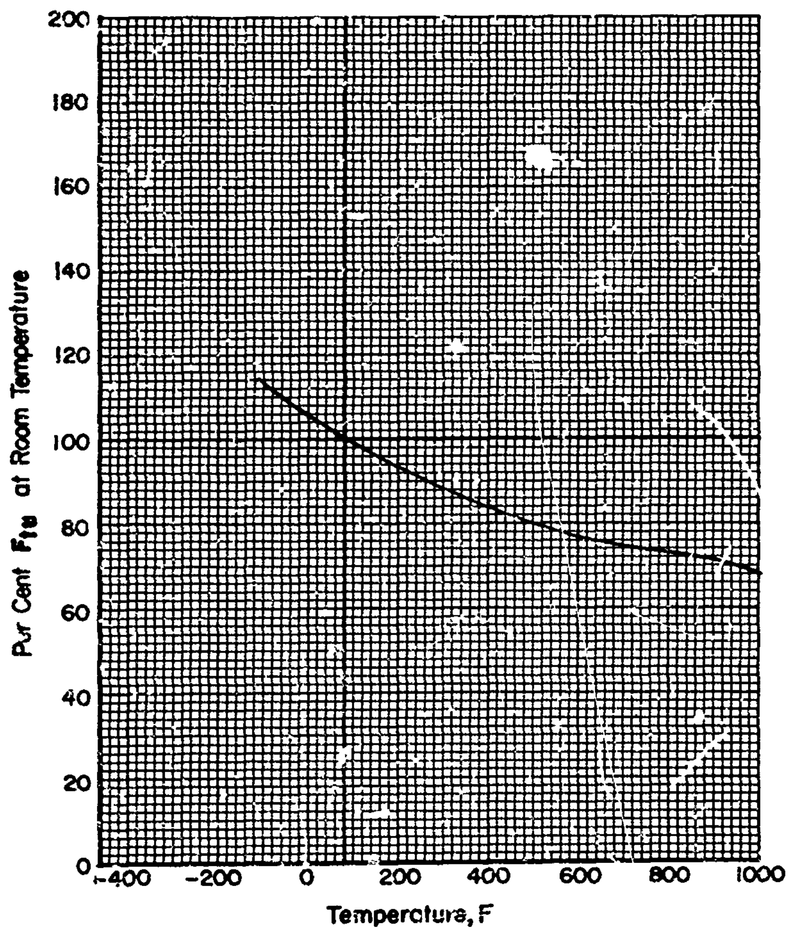

FIGURE 5-8.3.1-1. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF SOLUTION-TREATED AND AGED Ti-679 ALLOY BARS AND FORGINGS

OK PER MIL-5 GUIDELINES
BUT NOT APPROVED BY MIL-5

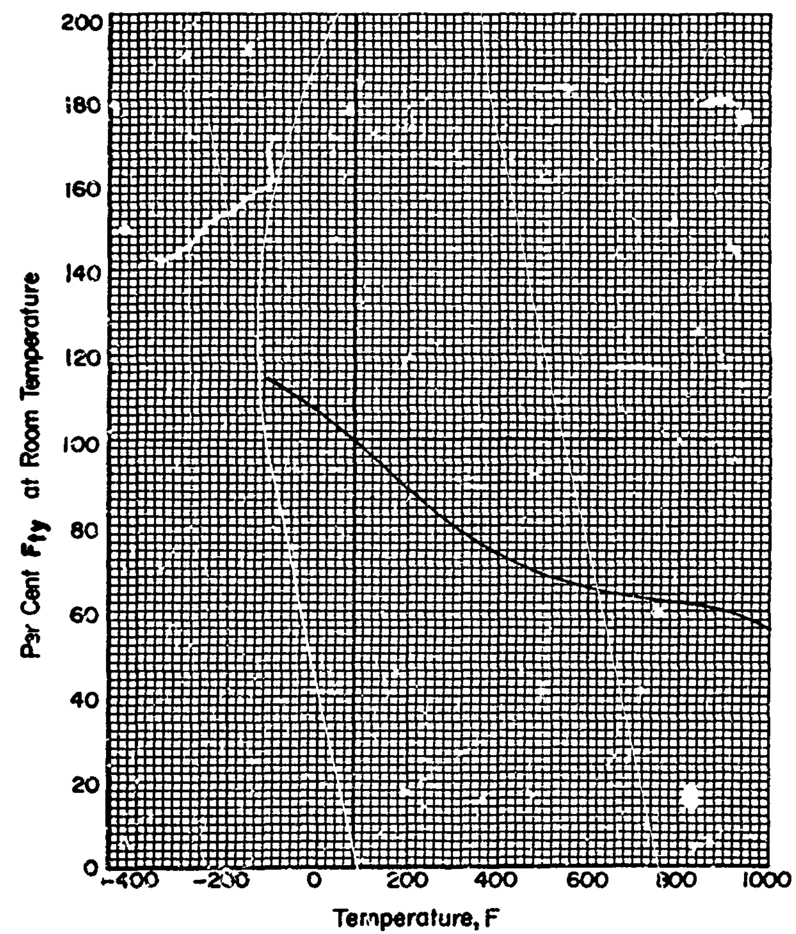

FIGURE 5-8.3.1-2. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF SOLUTION-TREATED AND AGED Ti-679 ALLOY BARS AND FORGINGS

OK PER MIL-5 GUIDELINES
BUT NOT APPROVED BY MIL-5

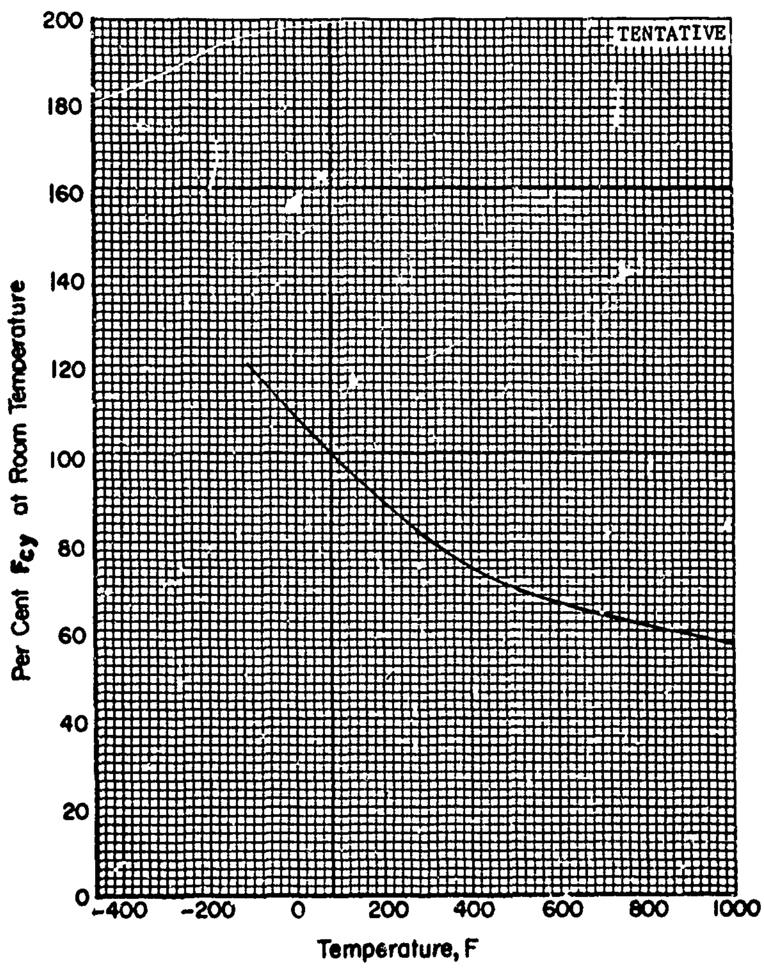

FIGURE 5-C.3.1-3. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF SOLUTION-TREATED AND AGED Ti-679 ALLOY BARS AND FORGINGS

(TENTATIVE CURVE BASED ON LIMITED DATA)

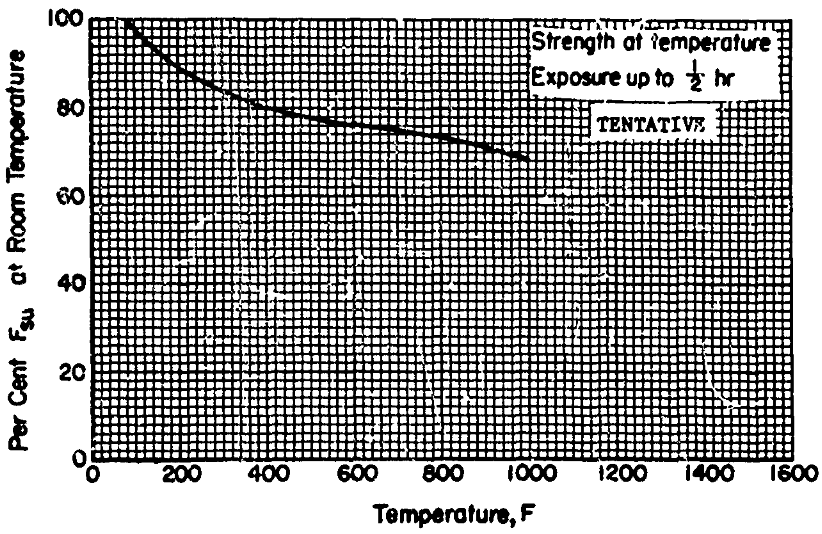

FIGURE 5-8.3.1-4. EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF SOLUTION-TREATED AND AGED Ti-679 ALLOY BAR AND FORGING (TENTATIVE CURVE BASED ON LIMITED DATA) (49,53)

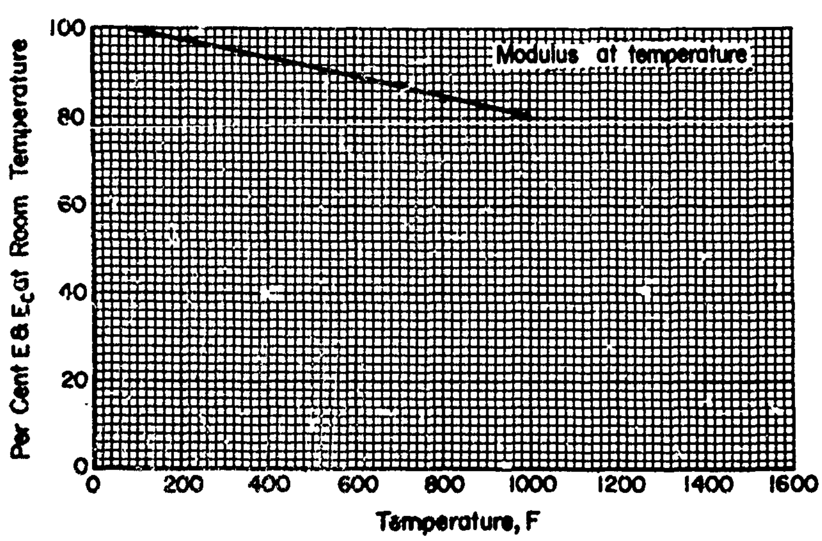

FIGURE 5-8.3.1-7. EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E AND E_c) OF SOLUTION TREATED AND AGED Ti-679 ALLOY BAR AND FORGINGS[53]

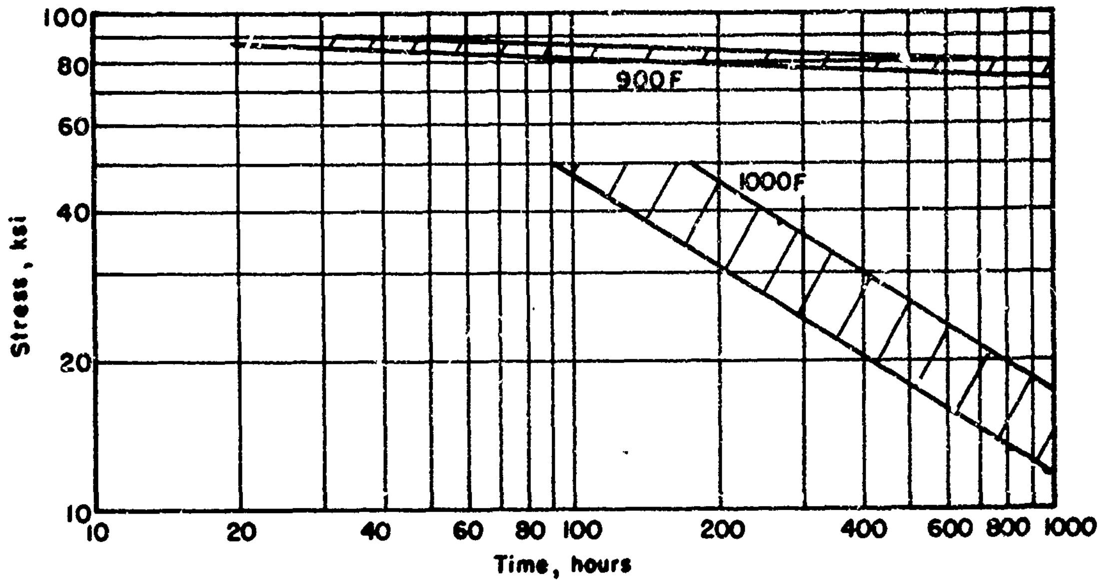

FIGURE 5-8.3.4-1. TYPICAL 1.0% DEFORMATION CREEP PROPERTIES OF SOLUTION TREATED AND AGED Ti-679[53]

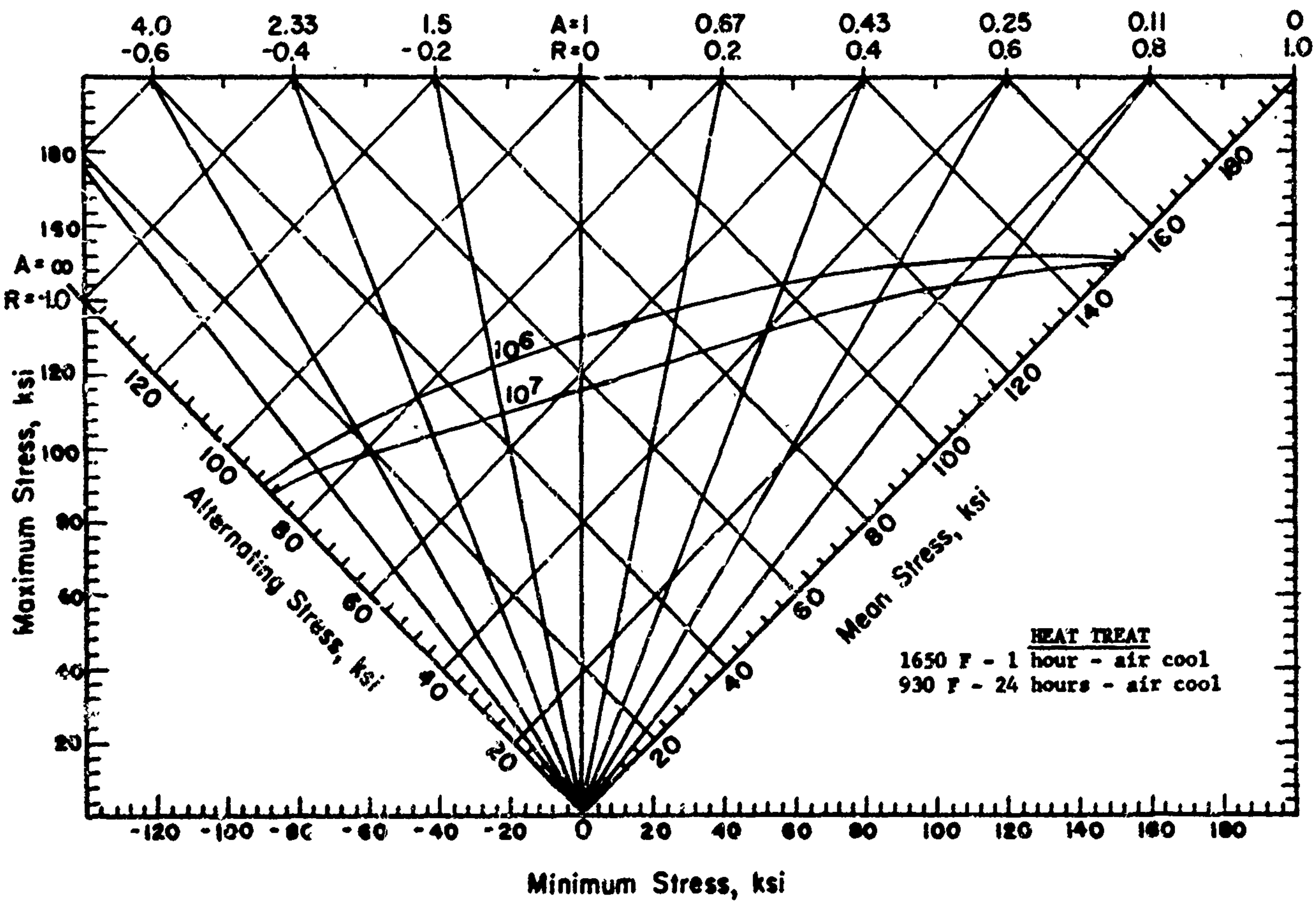

FIGURE 5-8.3.5-1. CONSTANT-LIFE FATIGUE DIAGRAM FOR Ti-679 FORGING TESTED AT ROOM TEMPERATURE AT A FREQUENCY OF 1800 CPM IN BENDING[67]

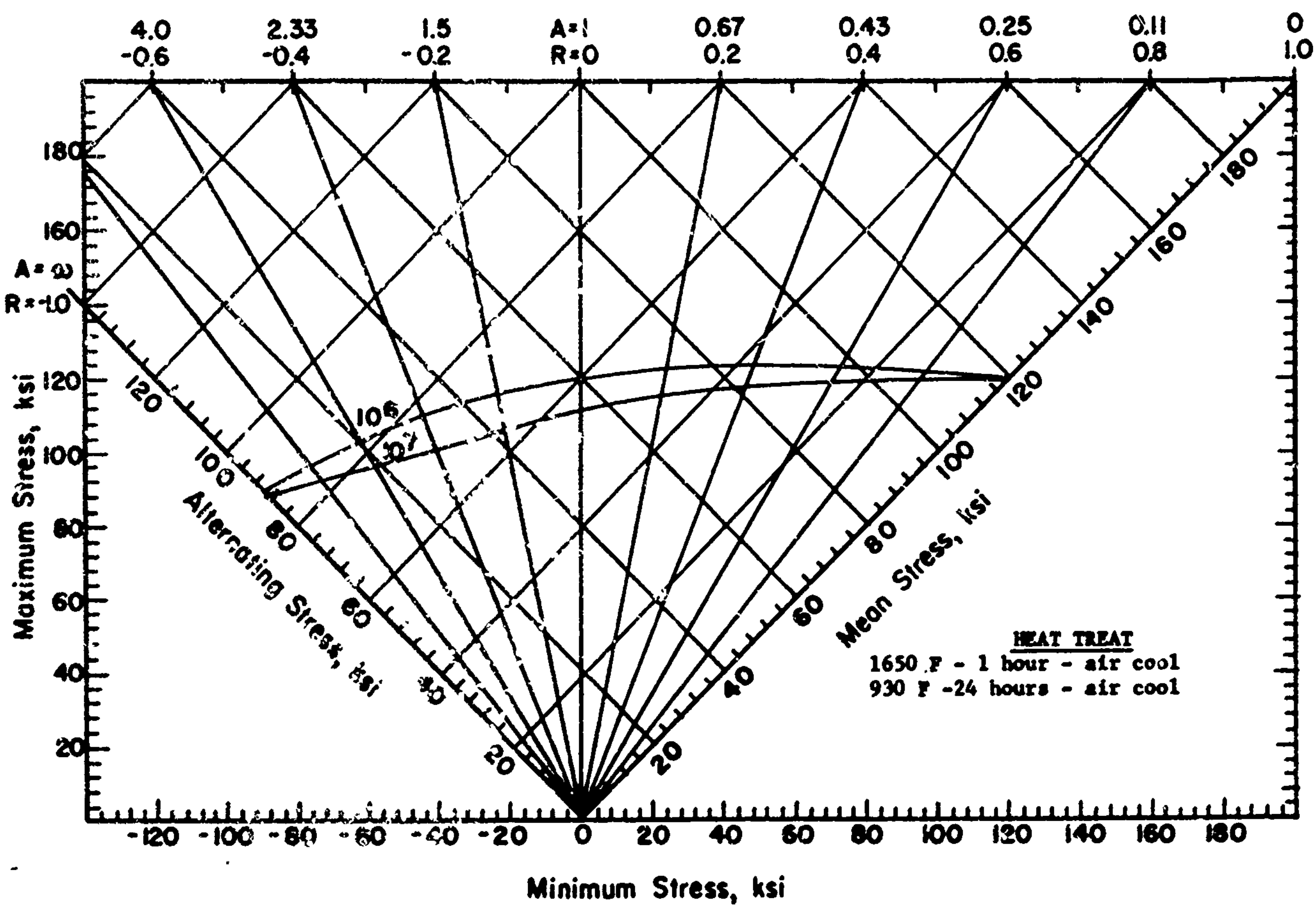

FIGURE 5-8.3.5-2. CONSTANT-LIFE FATIGUE DIAGRAM FOR Ti-679 FORGING TESTED AT 500 F AT A FREQUENCY OF 1800 CPM IN BENDING(67)

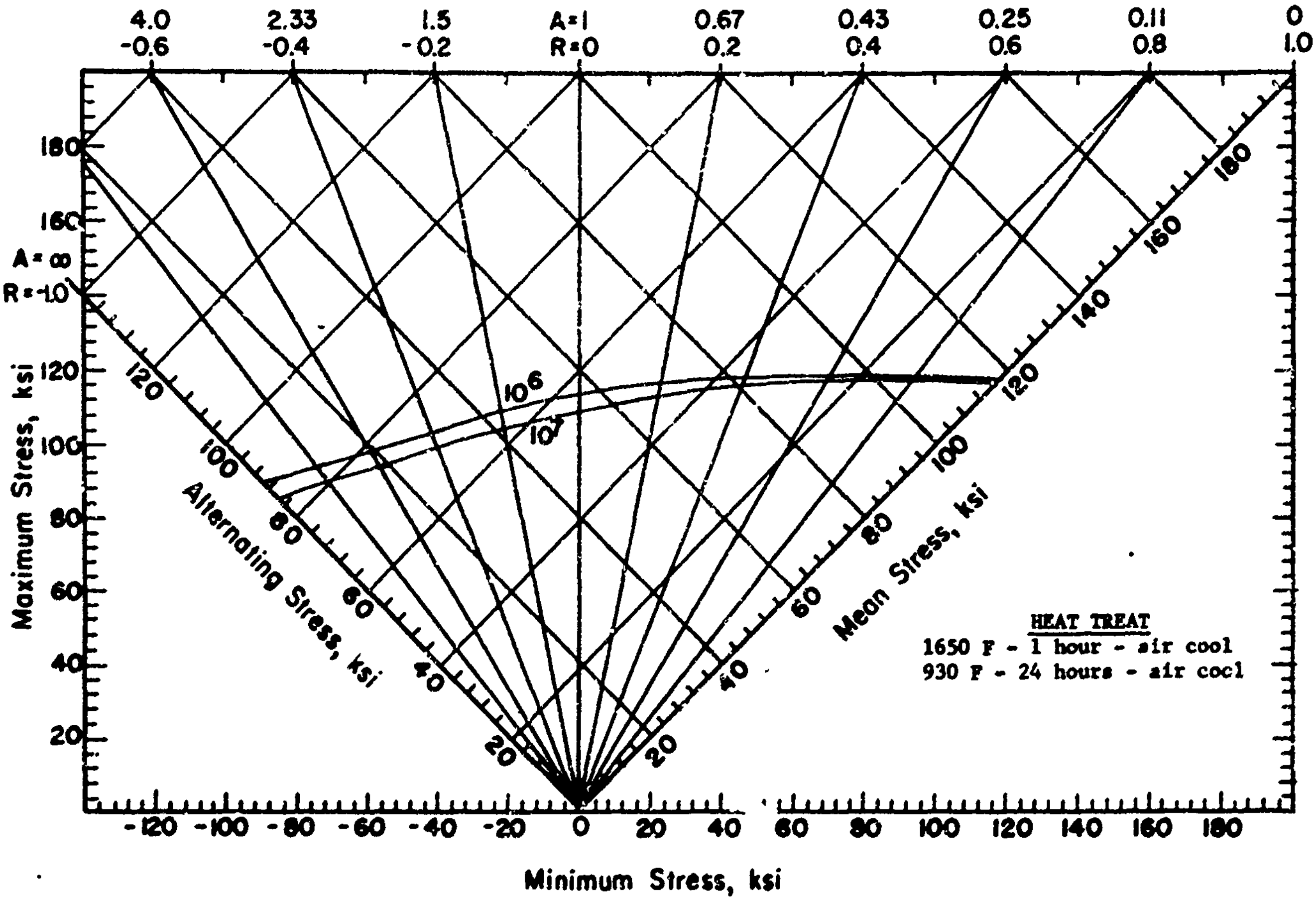

FIGURE 5-8.3.5-3. CONSTANT-LIFE FATIGUE DIAGRAM FOR Ti-679 FORGING TESTED AT 800 F AT A FREQUENCY OF 1800 CPM IN BENDING(67)

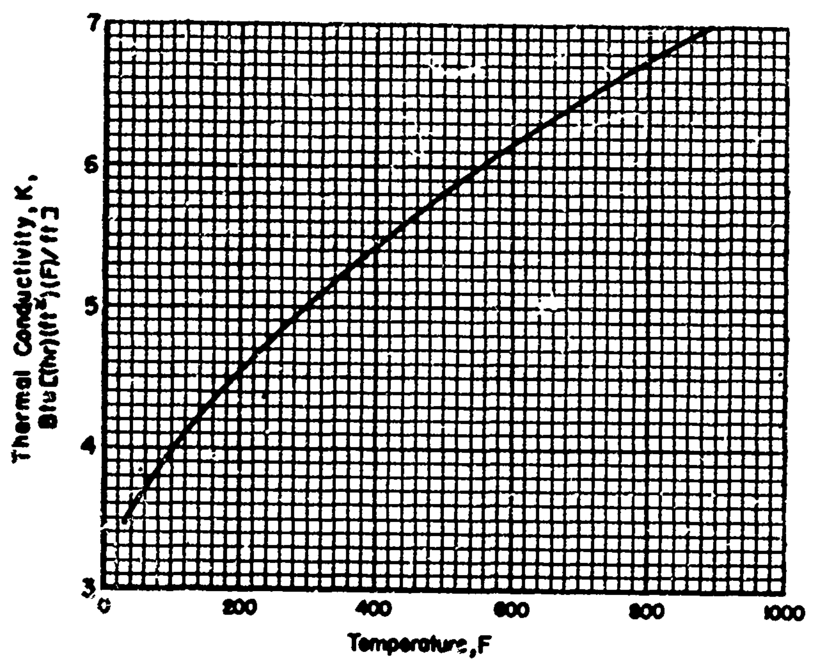

FIGURE 5-8.4-2. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY (K) OF Ti-679(48)

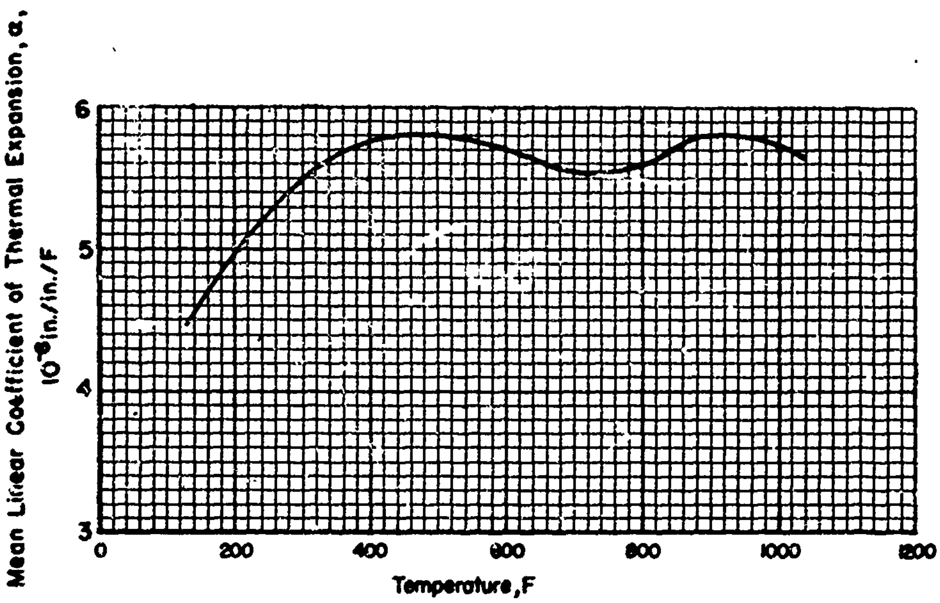

FIGURE 5-8.4-3. MEAN LINEAR COEFFECIENT OF THERMAL EXPANSION (α) OF Ti-679 BETWEEN ROOM TEMPERATURE AND THE INDICATED TEMPERATURE (48)

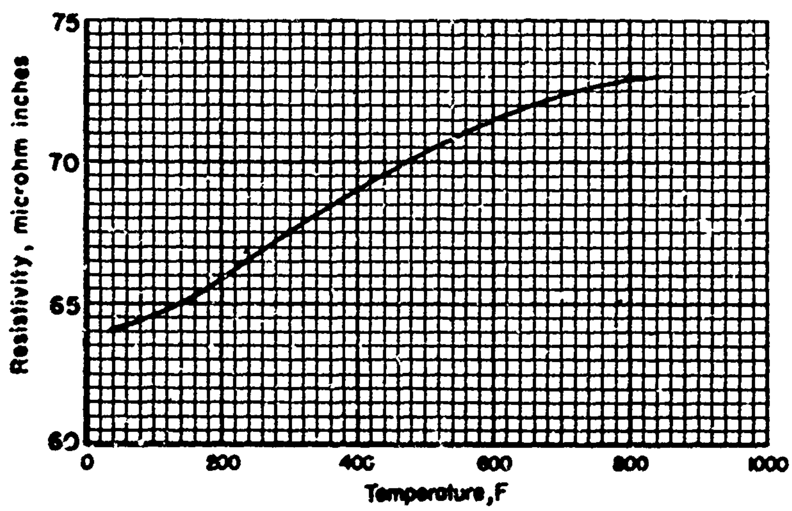

FIGURE 5-8.4-4. EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY (ρ) OF Ti-679 (48)

5-9 Titanium Alloy Ti-6Al-2Sn-4Zr-2Mo

5-9.0 SPECIFICATIONS AND FORMS

This section covers titanium alloy Ti-6Al-2Sn-4Zr-2Mo of the following specifications and forms:

Specification	Form
-------	Sheet
MIL-T-9047	Bars and forgings

5-9.1 ROOM-TEMPERATURE DESIGN MECHANICAL PROPERTIES

Table 5-9.1-1 summarizes the design mechanical properties of titanium alloy Ti-6Al-2Sn-4Zr-2Mo in all product forms.

5-9.2 ENVIRONMENTAL EFFECTS FOR DUPLEX-ANNEALED MATERIAL

5-9.2.1 Elevated-Temperature Effects

The effect of temperature data are presented in Figures 5-9.2.1-1 through 5-9.2.1-7.

5-9.2.5 Fatigue Effects

Constant-life diagrams for fatigue behavior are presented in Figures 5-9.2.5-1 through 5-9.2.5-3.

Note: This alloy is not included in MIL-HDBK-5.

[illegible]

Alloy	Ti-6Al-2Sn-4Zr-2Mo	MIL-T-9047 Type III Composition I	
Form	Sheet	Bars and forgings	
Condition	Duplex annealed	Annealed per MIL-H-21800	
Thickness or diameter, in.	<0.187	≤2[b]	>2, ≤4[b]
Basis	S[a]	S	S
Mechanical properties:			
F_{tu}, ksi	[illegible]	130	130
L	[illegible]		
T	[illegible]		
F_{ty}, ksi	[illegible]	120	120
L	[illegible]		
T	[illegible]		
F_{cy}, ksi	[illegible]	---	---
L	[illegible]		
T	[illegible]		
F_{su}, ksi	[illegible]	---	---
F_{bru}, ksi:			
(e/D = 1.5)	[illegible]	[illegible]	---
(e/D = 2.0)	[illegible]	[illegible]	---
F_{bry}, ksi:			
(e/D = 1.5)	[illegible]	[illegible]	---
(e/D = 2.0)	[illegible]	[illegible]	---
e, per cent:			
L	[illegible]	[illegible]	[illegible]
T	[illegible]	[illegible]	[illegible]
E, 10^6 psi	(16)	---	
E_c, 10^6 psi	---	---	
G, 10^6 psi	---	---	
μ	0.32	---	
α	---	---	
ω, lb/in.^{3}	0.164		

Parentheses () indicate tentative values based on limited data.

a Producer's guaranteed minimums for F_{tu}, F_{ty}, and e.
b Width ≤ 8.

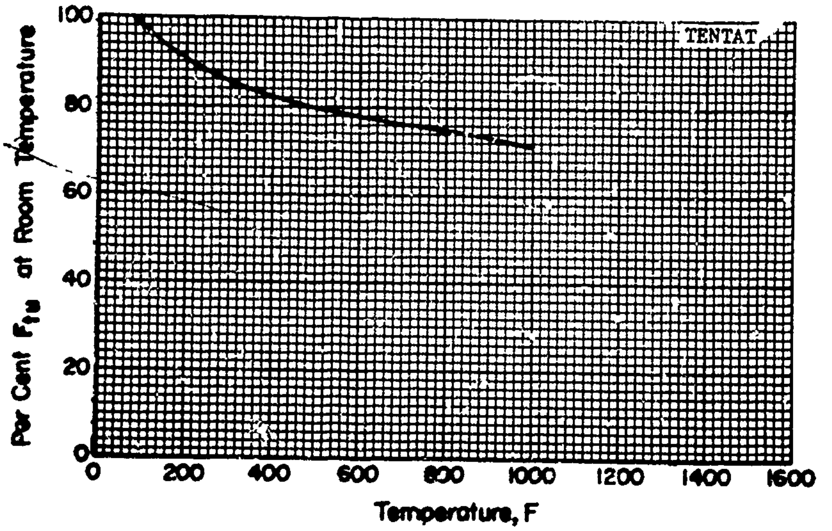

FIGURE 5-9.2.1-1 EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH (F_{tu}) OF DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET. (TENTATIVE CURVE BASED ON LIMITED DATA).[55]

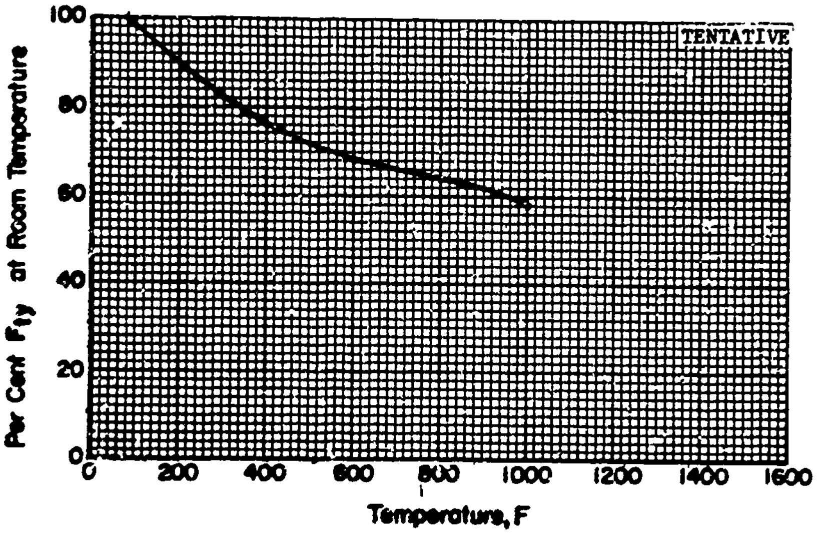

FIGURE 5-9.2.1-2 EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET. (TENTATIVE CURVE BASED ON LIMITED DATA).[55]

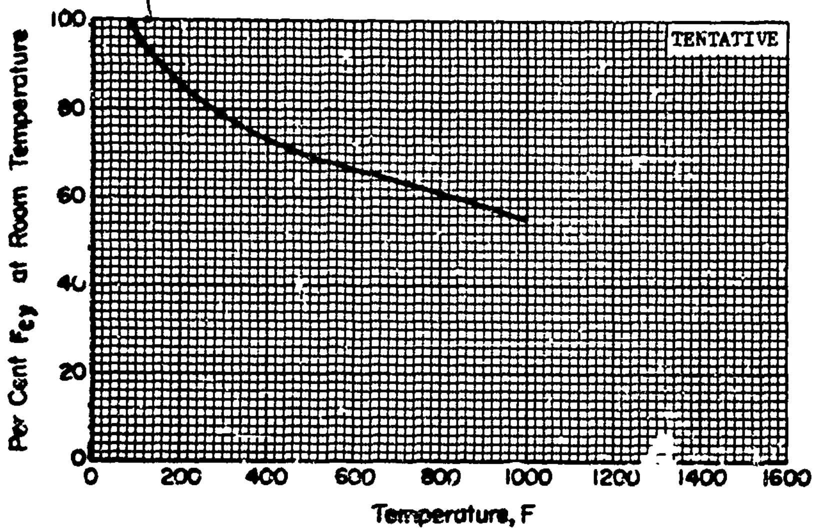

FIGURE 5-9.2.1-3 EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH (F_{cy}) OF DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET. (TENTATIVE CURVE BASED ON LIMITED DATA).[55]

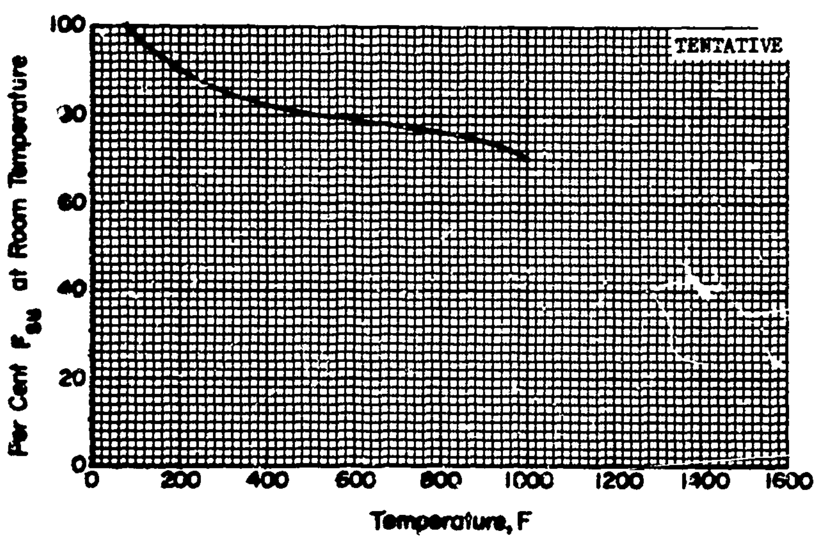

FIGURE 5-9.2.1-4 EFFECT OF TEMPERATURE ON THE ULTIMATE SHEAR STRENGTH (F_{su}) OF DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET. (TENTATIVE CURVE BASED ON LIMITED DATA).[55]

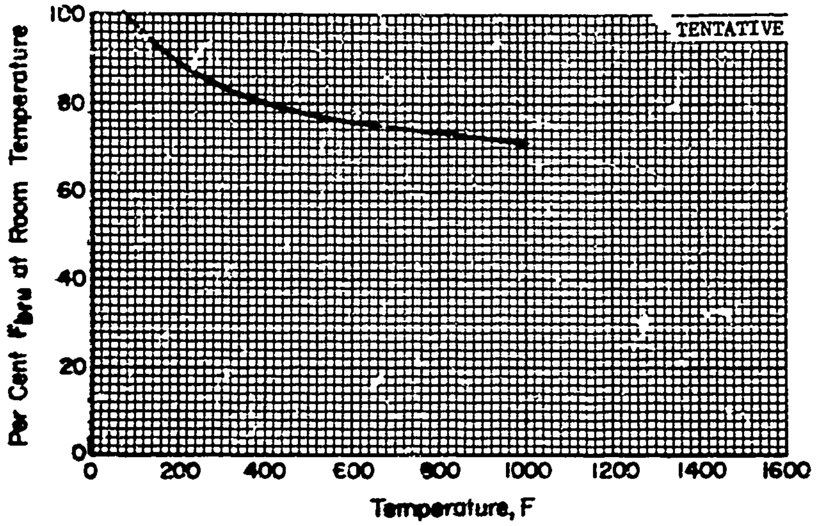

FIGURE 5-9.2.1-5 EFFECT OF TEMPERATURE ON THE ULTIMATE BEARING STRENGTH (F_{bru}) OF DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET. (TENTATIVE CURVE BASED ON LIMITED DATA).[55]

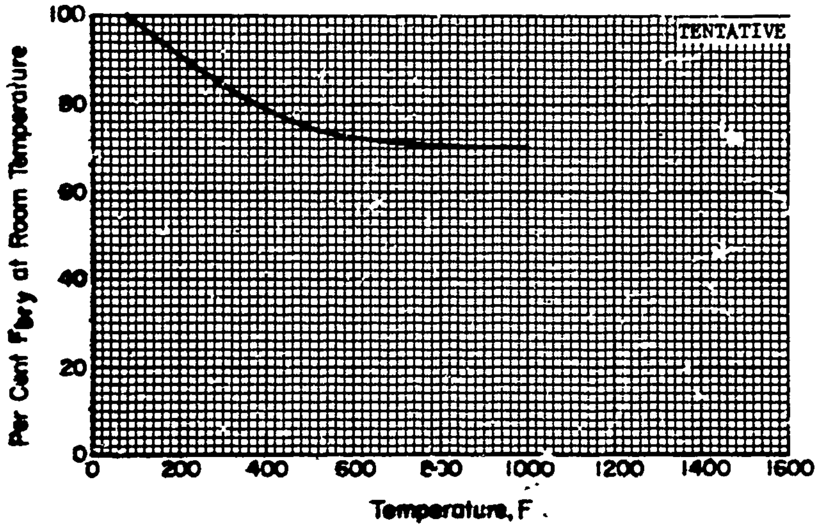

FIGURE 5-9.2.1-6 EFFECT OF TEMPERATURE ON THE BEARING YIELD STRENGTH (F_{bry}) OF DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET. (TENTATIVE CURVE BASED ON LIMITED DATA).[55]

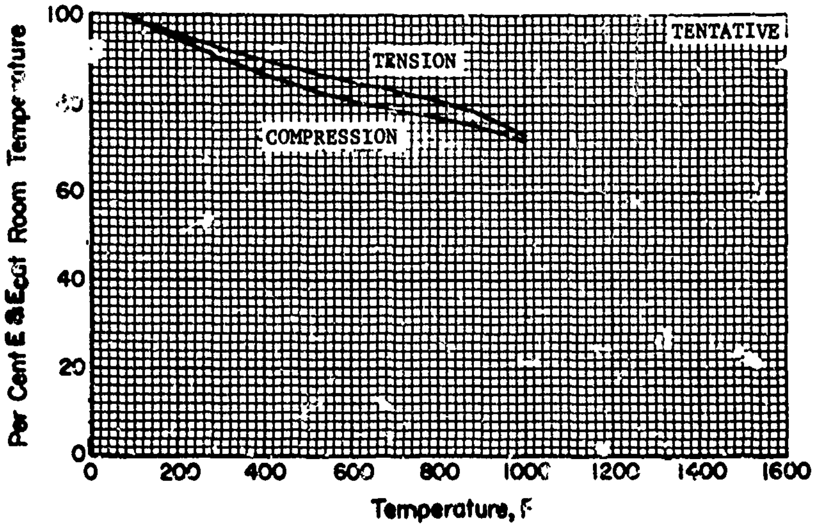

FIGURE 5-9.2.1-7 EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULUS (E and E_c) OF DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET. (TENTATIVE CURVES BASED ON LIMITED DATA).[55]

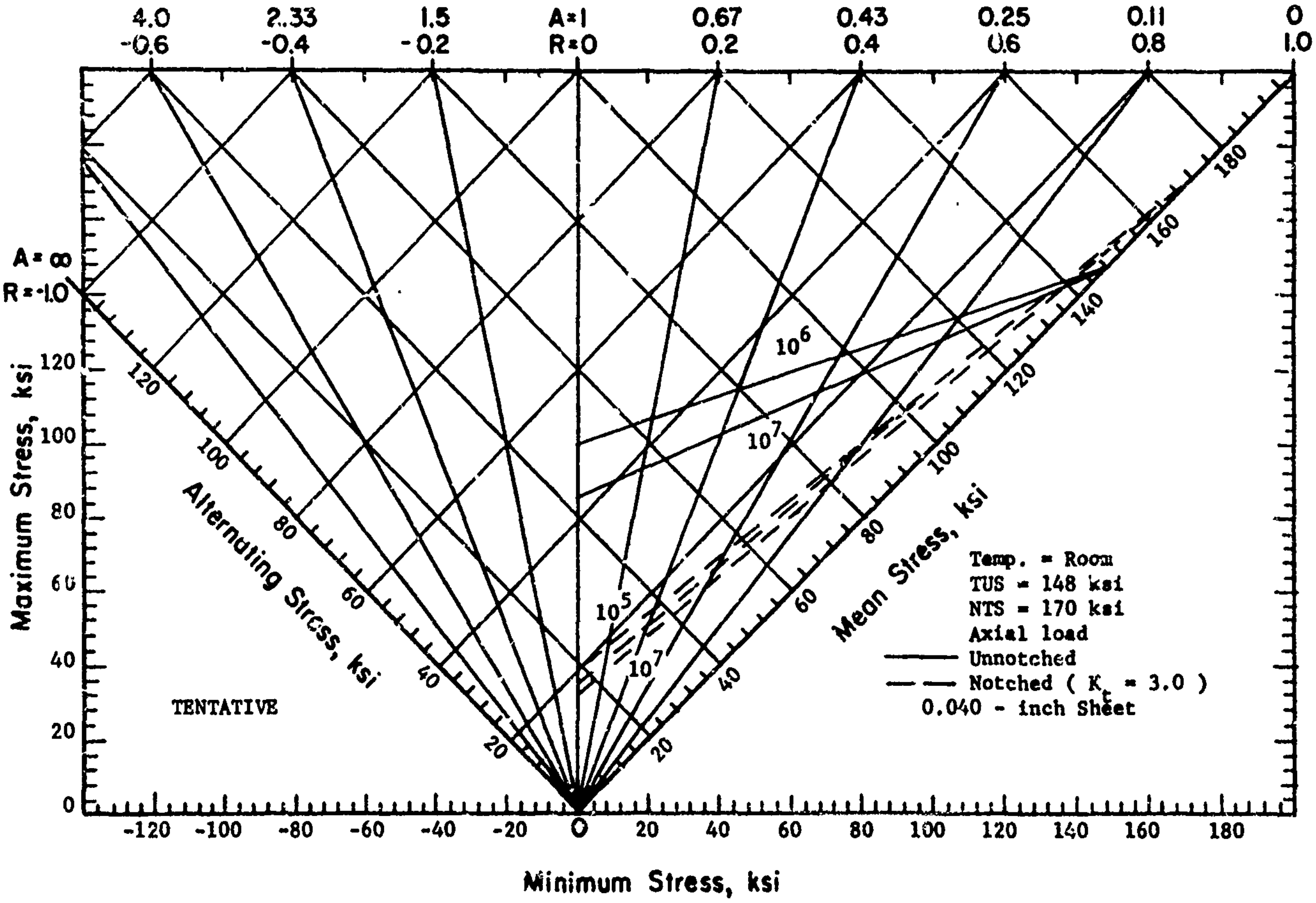

FIGURE 5-9.2.5-1. TENTATIVE CONSTANT-LIFE FATIGUE DIAGRAM FOR DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET AT ROOM TEMPERATURE.
(Tentative curves based on limited data).[55]

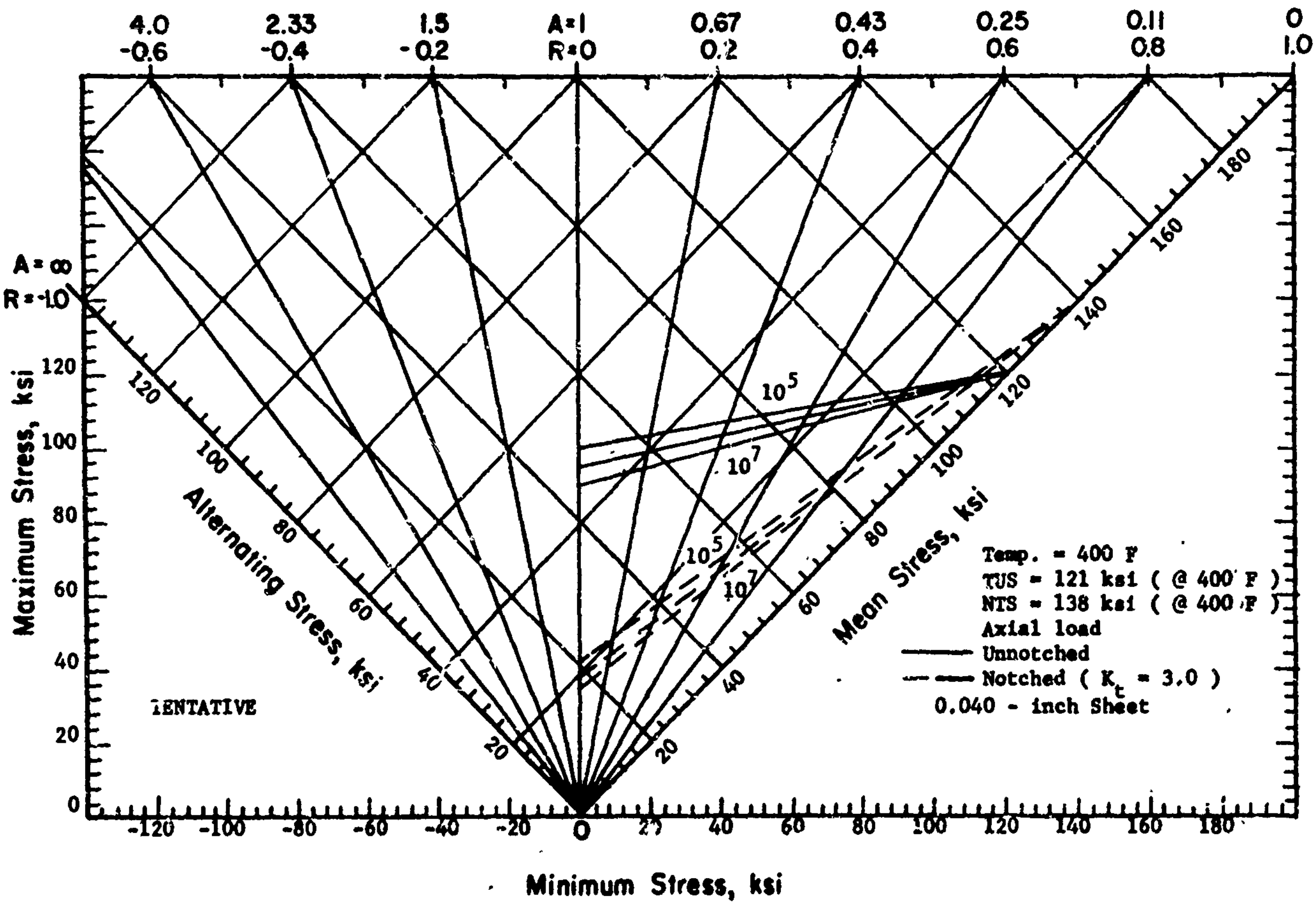

FIGURE 5-9.2.5-2. TENTATIVE CONSTANT-LIFE FATIGUE DIAGRAM FOR DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET AT 400 F.

(Tentative curves based on limited data).[55]

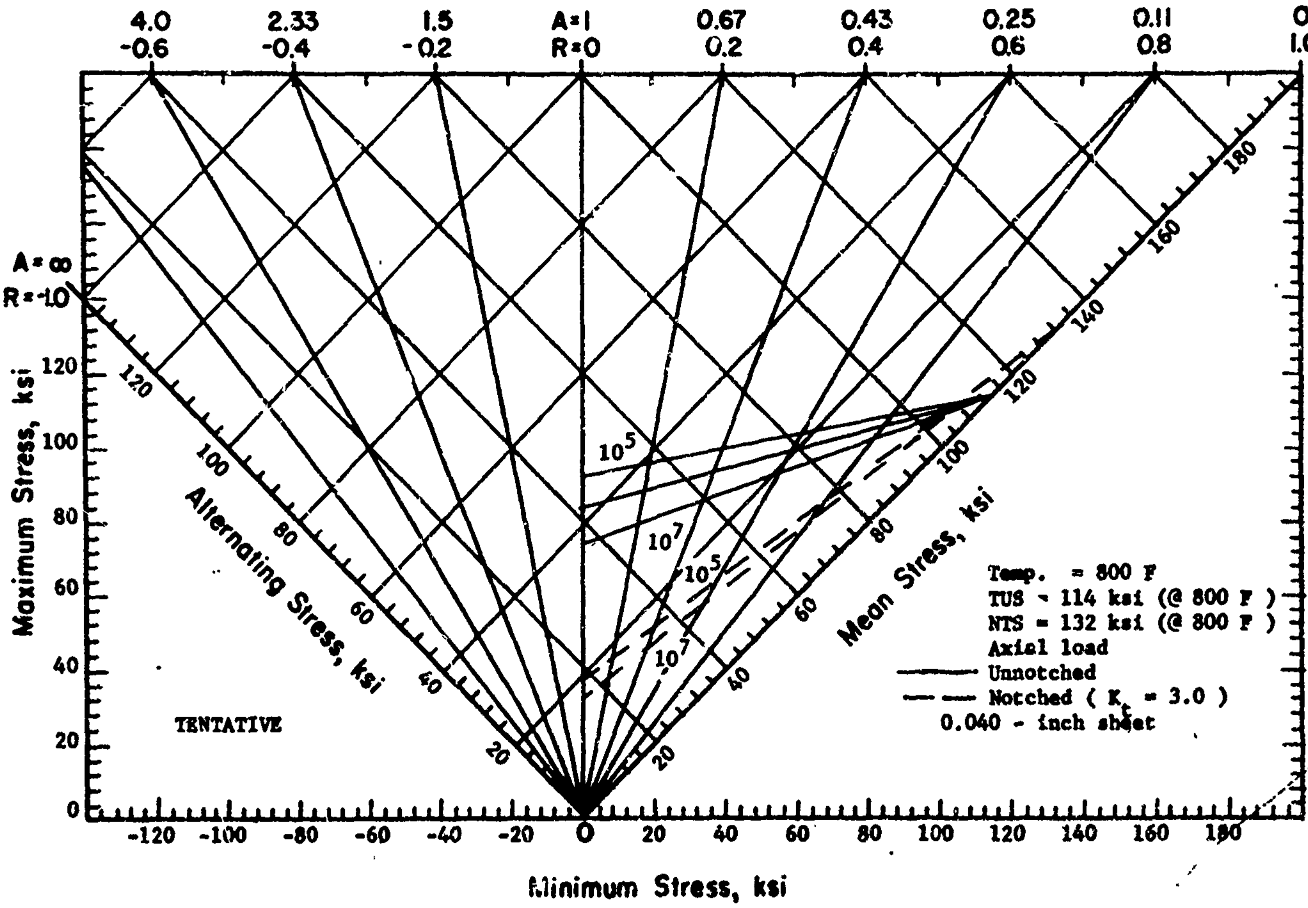

FIGURE 5-9.2.5-3. TENTATIVE CONSTANT-LIFE FATIGUE DIAGRAM FOR DUPLEX-ANNEALED Ti-6Al-2Sn-4Zr-2Mo SHEET AT 800 F.

(Tentative curves based on limited data).(55)

5-20 REFERENCES

(1) "Properties of Ti-6Al-4V", Titanium Metals Corporation of America, Titanium Bulletin No. 1 (January, 1957).

(2) "Properties of Ti-5Al-2.5Sn", Titanium Metals Corporation of America (April, 1958).

(3) "Crucible A-110AT Titanium Base Alloy", Crucible Steel Company Data Sheet (May, 1958).

(4) "Determination of Materials Design Criteria for 6Al-4V Titanium Alloy at Room and Elevated Temperatures", WADC-TR-58-246, Southwest Research Institute (May, 1958).

(5) "Engineering Properties of Commercial Titanium Alloys", Titanium Metallurgical Laboratory, Battelle Memorial Institute, TML Report No. 92, Defense Metals Information Center, Columbus, Ohio (June, 1958).

(6) "Crucible A-40, A-55, A-70 Commercially Pure Titanium", Crucible Steel Company Data Sheet (1960).

(7) "DOD High Strength Titanium Alloy Sheet Research Program", North American Aviation, Columbus Division (August, 1960).

(8) "Evaluation of New Titanium Sheet Alloys for Use in Airframe Construction", AMC-TR-60-7-561, North American Aviation, Los Angeles Division (December, 1960).

(9) "Crucible C-120AV Titanium Base Alloy", Crucible Steel Company Data Sheet (1961).

(10) "Evaluation of New High Strength Titanium Sheet Alloys", Chance-Vought Aircraft Company (April, 1961).

(11) "Titanium Development Program", ASD-TR-61-7-576, General Dynamics Corporation, Convair Division (May, 1961).

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13. ABSTRACT

This represents a second edition of an earlier handbook bearing the same title and the designation SST 65-8, dated August, 1965. The handbook represents a collection of data from many sources on the properties and fabrication characteristics of commercially pure titanium and eight titanium alloys including Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-13V-11Cr-3Al, Ti-4Al-3Mo-1V, Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si and Ti-6Al-2Sn-4Zr-2Mo. Section 1 describes the metallurgical characteristics of titanium and these alloys. Section 2, 3, and 4 concern themselves with the availability of mill products, machining, and joining technology, respectively. Section 5 treats the subject of mechanical properties for these materials in a manner patterned after MIL-Handbook 5.

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